

# HYDROGEOLOGY OF THICK TILL DEPOSITS IN CONNECTICUT

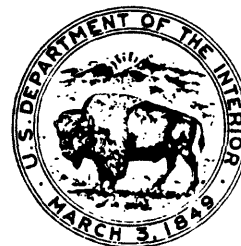
By Robert L. Melvin, Byron D. Stone, Janet R. Stone, and Newell J. Trask

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U.S. GEOLOGICAL SURVEY

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## CONTENTS

	Page
Abstract.....	1
Introduction.....	3
Purpose and scope.....	3
Hydrogeologic considerations for a low-level radioactive-waste disposal facility.....	4
Acknowledgments.....	5
Physical setting.....	5
Physiography and bedrock geology.....	5
Distribution of surficial materials.....	7
Climate and hydrology.....	8
Hydrogeology of thick-till deposits in Connecticut.....	12
Lithostratigraphic units.....	12
Distribution of deposits.....	14
Surface (upper) till.....	14
Drumlin (lower) till.....	14
Genesis and age of deposits.....	15
Physical characteristics of deposits.....	16
Surface (upper) till.....	16
Color and mineralogy.....	16
Grain size.....	16
Geotechnical classification.....	17
Layering, fabric, and structure.....	17
Weathering and soils.....	17
Drumlin (lower) till.....	20
Color and mineralogy.....	20
Grain size.....	20
Geotechnical classification.....	21
Layering, fabric, and structure.....	21
Weathered zone.....	22
Ground-water recharge, discharge, and circulation in till areas...	22
Position of the water table.....	25
Hydraulic properties of deposits.....	27
Heterogeneity.....	29
Anisotropy.....	31
Flow of water through till.....	31
Summary and conclusions.....	34
References cited.....	37
Appendix A: Specific site-suitability requirements that relate to hydrogeology.....	43

## ILLUSTRATIONS

	Page
Figure 1. Map showing physiographic divisions and bedrock geology of Connecticut.....	6
2. Map showing principal aquifers in Connecticut.....	9
3. Schematic distribution and relation of surface tills (late Wisconsinan), drumlin tills (Illinoian), weathered zone at top of drumlin till, and mixed-till zones of the surface tills.....	13

## ILLUSTRATIONS--continued

	Page
4. Ternary diagrams showing sand-silt-clay content of the matrix of surface and drumlin tills in Connecticut.....	18
5. Hydrogeologic section showing water-table configuration in a thick-till hillside in eastern Connecticut.....	24
6. Graph showing average monthly maximum and minimum water levels and median water levels, in U.S. Geological Survey observation well MF-1, July 1946 to November 1991.....	26
7. Vertical profiles of hydraulic conductivity.....	30

## TABLES

	Page
Table 1. Representative values of hydraulic properties of hydrogeologic units in Connecticut.....	10
2. Long-term observations of water levels in selected Connecticut wells in till.....	25
3. Estimated distance that water would flow through a homogeneous till matrix during a 100-year period.....	33

## CONVERSION FACTORS

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
inch (in.)	25.4	millimeter (mm)
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
foot per day (ft/d)	0.0003528	centimeter per second (cm/s)

Scientific notation--A method of expressing a number by giving only the significant figures and indicating multiplication by the proper power of 10. For example,  $2.5 \times 10^{-3} = 0.0025$

Sea level--In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)- a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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## ABSTRACT

Thick-till deposits in Connecticut have been identified by the Connecticut Hazardous Waste Management Service as a hydrogeologically preferred setting for a low-level radioactive-waste disposal site. These deposits are found throughout the State, and the thickest compose drumlins. Till in Connecticut is texturally variable, but most varieties are sandy, consisting of a nonsorted matrix of sand, silt, and clay that contains scattered gravel clasts. Till overlies fractured crystalline (metamorphic and igneous) bedrock in the western and eastern uplands, and fractured sedimentary and igneous bedrock in the central lowland of the State. In areas of thick till in drumlins and related deposits, thickness of compact till exceeds 15 ft (feet) (4.6 m (meters)). In other areas, till is less than 15 ft (4.6 m) thick, and bedrock outcrops are numerous.

Two tills of two ages and with different physical characteristics are recognized in Connecticut. The late Wisconsinan surface till forms an irregular mantle over bedrock, generally less than 15 ft (4.6 m) thick. Surface till is compact and silty in most areas and loose and sandy at the land surface locally. The color, mineral composition, and grain-size distribution of the surface till are related to the local bedrock source. The matrix of the surface till derived from crystalline rocks contains an average of 66-percent sand, but where derived from marble and schist, the matrix is silty, containing as much as 72-percent silt. Compact surface tills appear massive, without fractures. In the central lowland, the matrix of the reddish-brown surface till, largely derived from the underlying sedimentary bedrock, is silty sand, with average sand content of 52 percent.

The Illinoian compact till which forms the bulk of drumlins and other thick-till areas is referred to as the drumlin till. Drumlin till is generally thicker than 15 ft (4.6 m) and commonly more than 100 ft (30 m) thick in drumlins. In crystalline-rock areas, this till is dark gray; in sedimentary-rock areas, the drumlin till is reddish brown or red. The matrix of drumlin till derived from coarse-grained crystalline rocks has an average sand content of 57 percent and a clay content that is generally more than 10 percent and as much as 25 percent. The matrix of drumlin tills derived from marble and schist contains more than 50-percent combined silt and clay and as much as 64-percent silt. The drumlin till is very compact and appears generally massive and homogeneous in deep exposures. The drumlin till is weathered to depths of 20 to 37 ft (6.1 to 11.3 m) below the land surface; subhorizontal and subvertical fractures are numerous and closely spaced in the upper part of the weathered zone. Weathering effects, such as leaching, alteration of clay minerals, and oxidation of iron-bearing minerals, increase progressively upward through the weathered zone.

Recharge of ground water in till, estimated from hydrologic budgets of small watersheds, exceeds 5.7 in/yr (inches per year) (14.5 cm/yr (centimeters per year)). Flow paths from recharge areas of the ground-water flow system in thick till to discharge areas, such as streams and swamps, are likely to range from several hundred to several thousand feet, but much smaller local flow systems with flow paths measuring tens of feet may also be present. The water table in till is generally within 10 to 15 ft (3 to 4.6 m) of the land surface and is rarely deeper than 40 ft (12.2 m). A range of fluctuation of 8 to 17 ft (2.4 to 5.2 m) over periods of 1 or more years is commonly observed.

Available data, although sparse, indicate that values of hydraulic conductivity of Connecticut tills are commonly in the range of  $1 \times 10^{-3}$  to 24 ft/d (feet per day) ( $3.7 \times 10^{-7}$  to  $8.5 \times 10^{-3}$  cm/s (centimeters per second)) and porosities are commonly in the range of 20 to 35 percent. The lower values of hydraulic conductivity are generally associated with compact surface tills and drumlin tills that are derived from sedimentary rocks. Widely observed sedimentological and structural features of Connecticut tills, such as lenses of stratified sediment and fractures, can produce heterogeneity and anisotropy.

No conclusions about the suitability of Connecticut tills for siting a low-level radioactive-waste disposal facility can be made from the current information. Such conclusions must rely on detailed site characterization. Many important elements of the hydrogeology of thick-till deposits, such as the hydrology of the unsaturated zone or the mineralogy of the deposits, have had little or no study. This lack of general knowledge will affect the scope and complexity of site-characterization studies.

## INTRODUCTION

The Low-Level Radioactive Waste Policy Act of 1980, as amended by the Low-Level Radioactive Waste Policy Amendments Act of 1985, requires States or Compacts of States to locate new disposal facilities by 1993 or lose their access to existing low-level radioactive-waste disposal sites. Ten compacts and seven unaffiliated states are moving in various ways to meet these mandates.

In 1991, the Connecticut Hazardous Waste Management Service identified several locations in Connecticut as potential sites for a low-level radioactive-waste disposal facility. The potential sites are areas known or inferred to be underlain by till deposits greater than 10 to 15 ft (3 to 4.6 m) thick, shown as thick-till areas on the Surficial Materials Map of Connecticut (Stone and others, in press). Most of the thick till is present in drumlins and related glacial landforms. Three candidate sites to be investigated are in north-central Connecticut (Connecticut Hazardous Waste Management Service, 1991) where the till was derived largely from glacial erosion of Mesozoic sedimentary rocks.

The Connecticut Department of Environmental Protection (DEP) has been asked by the Governor of Connecticut to identify any environmental concerns they have about the potential disposal sites. To address any concerns that might be affected by hydrogeologic factors, the U.S. Geological Survey (USGS), in cooperation with the DEP, reviewed and summarized information on the hydrogeology of thick-till areas in Connecticut, particularly information that may relate to ground-water flow and transport of contaminants from a low-level radioactive-waste disposal facility.

### Purpose and Scope

The purpose of this report is to summarize available information on the hydrogeology of drumlins and other thick-till deposits in Connecticut, particularly information that relates to the subsurface flow of ground water and transport of associated contaminants. By describing the physical and hydraulic characteristics of the tills and the hydrogeologic processes in thick-till areas, and by indicating where current knowledge is sparse or unreliable, the report identifies areas of concern and provides a framework for design of subsequent site-characterization studies. This summary of hydrogeologic information, however, cannot substitute for detailed investigations at specific sites.

Published sources of data and unpublished University theses that were reviewed are listed in the references section of the report. Unpublished data from the USGS and U.S. Department of Agriculture, Soil Conservation Service (SCS) were also reviewed and data from these sources are acknowledged in the text. The numerical values taken from these published and unpublished sources are in several different inch-pound and metric (International System) units. The values have been converted to consistent inch-pound units followed by metric equivalents for this report.

## Hydrogeologic Considerations for a Low-Level Radioactive-Waste Disposal Facility

The Nuclear Regulatory Commission (NRC) has promulgated regulations for the siting, licensing, and operation of new low-level radioactive-waste disposal facilities (Code of Federal Regulations, Chapter 10, Part 61 (10 CFR 61) (U.S. Nuclear Regulatory Commission, 1982). In section 61.41, these regulations specify the maximum risk that can occur from the operation of a low-level radioactive-waste disposal facility as follows:

...the concentration of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public. Reasonable effort should be made to maintain release of radioactivity in effluents to the general environment as low as is reasonably achievable."

In addition, specific site-suitability requirements related to hydrogeology are specified in 10 CFR 61. These are listed in Appendix A. The focus of these regulations, issued in 1982, is on shallow land burial (below grade and either entirely above or below the water table). Subsequent to their release, the Low-Level Radioactive Waste Policy Amendments Act of 1985 encouraged engineered alternatives to shallow land burial and directed the NRC to develop policy that would allow such alternatives to be considered in the licensing process. Alternatives include below-ground vaults, above-ground vaults, use of modular concrete canisters disposed of below grade, and earth-mounded concrete bunkers above grade. The NRC has issued various guidance documents with regard to these engineered alternatives. However, the regulations cited concerning the hydrogeology of prospective sites still apply; whatever design is adopted for a low-level waste disposal facility, the site must still meet these requirements.

The Connecticut Hazardous Waste Management Service has also identified additional site-selection requirements and criteria that are related to hydrogeology (Connecticut Hazardous Waste Management Service, 1990, Appendix A). These additional requirements and criteria arise, in part, from the decision to provide capacity for mixed low-level radioactive and hazardous waste at a disposal facility, as well as from existing State statutes.

During the late 1970's and early 1980's, the USGS along with other Federal and State agencies conducted hydrogeologic studies of existing low-level radioactive-waste disposal sites, some of which had been closed because of operating problems. All of these sites employed shallow land burial. Generalizations and lessons learned from these studies have been reported by Fischer and Robertson (1984), Fischer (1986), Bedinger (1989), and in the proceedings of a workshop edited by Bedinger and Stevens (1990).

Facilities located at sites that meet the suitability requirements of 10 CFR 61 and that are properly constructed are expected to pose extremely low risks to the public. The problem, of course, is to find sites with these attributes and to design the facility so it is stable, is compatible with the local hydrogeology, and requires no long-term maintenance. Conclusions about the risks posed by specific sites are not possible until they have been thoroughly characterized, the hydrogeologic system is adequately understood, and the design of the facility has been established.



Adequate understanding will be required not only of the present undisturbed hydrogeologic system but also of the system after construction of the facility, including any effects due to emplacement of wastes in the immediate vicinity. Past problems at existing sites have resulted in large measure from a lack of understanding about how the disturbed hydrogeologic system would behave and from the absence of good engineering to avoid post-construction problems (Bedinger, 1989).

In Connecticut, the State Hazardous Waste Management Service is considering till deposits as potential sites for the location of a low-level radioactive-waste disposal facility. It is noteworthy that tills have been considered elsewhere as suitable media for disposal of low-level radioactive waste (Cherry and others, 1979). At the low-level radioactive-waste disposal site in West Valley, New York, migration of radionuclides through unweathered, fine-grained, low-permeability tills has been very negligible, although some radionuclides have migrated to the surface because of poor construction practices (Matuszek, 1988; Randall, 1990). Prudic (1990) has suggested that emplacement of low-level radioactive wastes below the water table in low-permeability tills in the humid northeastern United States, similar to those at West Valley, could provide a high degree of isolation of the wastes if the flow of ground water were minimal and molecular diffusion were the dominant mechanism for migration of radionuclides. Again, conclusions about the suitability of tills in Connecticut for either above or below ground disposal facilities cannot be based on these studies, but must rely on detailed site-specific investigations of the materials actually under consideration.

#### Acknowledgments

The authors appreciate the assistance of Dr. Harvey D. Luce of the University of Connecticut. Dr. Luce provided copies of unpublished University theses and unpublished data on till hydraulic properties and mineralogy from the SCS.

### PHYSICAL SETTING

#### Physiography and Bedrock Geology

The physiographic divisions of Connecticut are related to the underlying rock types (Rodgers, 1985) and their resistance to weathering and erosion. The central lowland (fig. 1) is underlain by nonresistant sedimentary rocks of the early Mesozoic Hartford basin. Rock units dip generally less than 20°, and sandstone units form long ridges parallel to strike that have moderate relief. In areas underlain by shale, glacial erosion has locally scoured the rock surface to below sea level (Ryder and Handman, 1973; Haeni and Sanders, 1974; Handman, 1975). Prominent strike ridges of resistant basalt and diabase divide the basin roughly into western and eastern segments. Areas of fractured rock associated with faults coincide with some local valleys in the lowland. Bedrock outcrops reveal that all rock units in the lowland are fractured by subvertical joints and joints that are parallel to bedding.

The western and eastern uplands of Connecticut are underlain by resistant crystalline-rock units of metamorphic and igneous origin. These rock units are widely fractured by faults, cleavage structures, and joints.

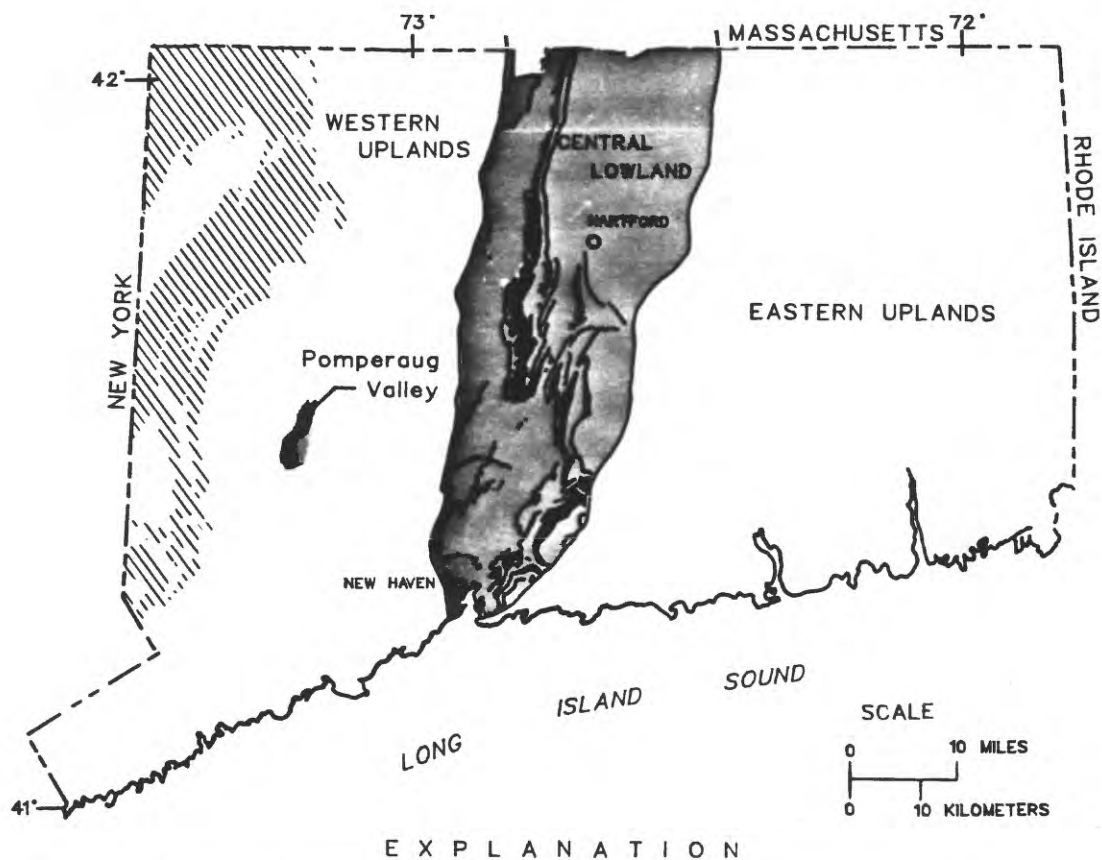


Figure 1.--Physiographic divisions and bedrock geology of Connecticut. (Modified from Fenneman, 1938; Rodgers, 1985; and Stone and others, 1985).

Fracture zones locally coincide with valley segments that are parallel to the strike of some units or that cut across the trend of units. Resistant, sparsely fractured, or flat-lying rock units underlie prominent ridges and hilltops. Glacial erosion has removed weathered materials from most upland areas; however, weathered-rock materials are preserved locally beneath thin glacial deposits (Agar, 1927; Schafer 1968; Pease 1970). Outcrops reveal that all rock units are fractured by subvertical joints and by joints that are parallel to the compositional layering in the rocks. In massive rocks, subhorizontal joints that closely parallel the land surface are related to erosional unloading of the rock surface.

In western Connecticut, marble rock units underlie deep valleys (fig. 1). Locally, deep depressions containing preglacially weathered residual materials (Ryder and others, 1970, p. 22; J.P. Schafer, U.S. Geological Survey, written commun., 1985) underlie the glacial deposits. Schist underlies extensive upland areas adjacent to the marble valleys.

### Distribution of Surficial Materials

The surficial materials which overlie the bedrock surface in Connecticut are predominantly deposits of continental glaciers that covered New England twice during the late Pleistocene Epoch. These materials range from less than 1 ft (0.3 m) to several hundred feet in thickness. The surficial materials comprise all nonlithified earth materials that commonly are referred to as "unconsolidated" soils in engineering literature. These materials lie below the modern pedogenic soil, which is composed of the A and B horizons (the solum).

The surficial materials of glacial origin are divided into two broad categories, till and stratified deposits (stratified drift). Till was deposited by glacier ice and is characterized by a nonsorted matrix of sand, silt, and clay with variable amounts of stones and large boulders. Stratified deposits are concentrated in valleys and were laid down by glacial meltwater in streams and lakes in front of the retreating ice margin during deglaciation. These deposits overlie the till and are characterized by layers of sorted gravel, sand, silt, and clay. The stratified deposits are divided into coarse-grained (fine sand to gravel) and fine-grained (very fine sand, silt, and clay). Postglacial floodplain alluvium, swamp, and marine beach deposits comprise the small remaining proportion of the surficial materials of Connecticut.

The distribution of surficial materials is shown on the Surficial Materials Map of Connecticut (Stone and others, 1985; in press). On this map, areas of till are differentiated as thick-till and thin-till areas on the basis of geologic interpretation of subsurface data and aerial photographs, published geologic maps, and field studies. Thin-till areas are underlain by a discontinuous mantle of till that is draped around bedrock outcrops and on top of linear topographic features that are oriented parallel to the trend of bedrock structural features. The till is loose to moderately compact, generally sandy, commonly stony, and less than 10 to 15 ft (3 to 4.6 m) thick. Thick-till areas are underlain by continuous till deposits in smooth, streamlined landforms, including ellipsoidal hills (drumlins) and till ramps on the northward-facing slopes of bedrock hills. Well and test-hole records collected in areas of thick till indicate that the till deposits are greater than 10 to 15 ft (3 to 4.6 m) thick. In drumlins, till deposits thicken from the outer edge to the central parts of the landforms where till thickness commonly exceeds 100 ft (30 m).

The areal distribution of surficial materials is related to the physiographic divisions of the State. In the western and eastern uplands, till is the major material, present as a discontinuous mantle of variable thickness (thin-till and thick-till areas) over the bedrock surface. Glacial stratified deposits, which overlie the till in upland valleys, commonly are 10 to 40 ft (3 to 12.2 m) thick and are composed chiefly of sand and gravel. In the central lowland, stratified deposits are the predominant surficial materials and generally overlie till. The extensive stratified deposits in the lowland are commonly 50 to 100 ft (15.2 to 30 m) thick and include glaciolacustrine silt and clay deposits, commonly 50 to 100 ft (15.2 to 30 m) thick (Langer, 1979). In the northern part of the lowland, stratified deposits almost completely cover the till-mantled bedrock surface. Drumlins are present as "islands" that are surrounded by stratified deposits.

### Climate and Hydrology

The climate of Connecticut is humid with an average annual precipitation of about 47 in. (119 cm) (Weiss and Cervione, 1986). In a 30-year period (1951-80), median annual precipitation ranged from about 53 in. (135 cm) in northwestern Connecticut to 40 in. (102 cm) in the southwestern part of the State, and analyses of longer periods of record indicate that precipitation in any given year can be considerably greater or less than the median (Hunter and Meade, 1983). For example, the median annual precipitation at Hartford for 1951-80 was about 44 in. (112 cm), but in 1965, the precipitation was only 28.44 in. (72 cm) and in 1972 it was 57.8 in. (147 cm) (Hunter and Meade, 1983, tables 3, 5, and 6).

Monthly precipitation is evenly distributed (generally 3 to 5 in. (7.6 to 12.7 cm) per month), although some seasonal variations occur. Extreme events are generally associated with intense storms of tropical origin. Several stations in Connecticut recorded more than 20 in. (51 cm) of precipitation in August 1955 as a consequence of two hurricanes (Hunter and Meade, 1983, table 6). Average annual runoff (1951-80) ranged from 22 to 29 in. (56 to 74 cm), while average annual evapotranspiration for the same period ranged from 22 to 27 in. (56 to 69 cm) (Weiss and Cervione, 1986).

Ground water is recharged mainly from precipitation that percolates from the land surface to the saturated zone. Recharge rates are variable, but the long-term average is estimated to range from about 7 to 20 in. (17.8 to 51 cm) per year (Melvin, 1985). Pumping of wells in areas near streams and lakes can induce large amounts of additional recharge from these surface-water bodies. Most ground-water flow occurs in the upper part of the saturated zone, generally within 300 ft (91 m) of the land surface. Because of the shallow depth of the flow system and the moderate topographic relief, the circulation of ground water in most parts of Connecticut is confined to the drainage basin of each perennial stream (Melvin, 1985).

Two principal types of aquifers underlie Connecticut--unconsolidated stratified-drift aquifers composed of sand and gravel, and bedrock aquifers composed of sedimentary, igneous, and metamorphic rocks. The distribution of these aquifers is shown in figure 2, and their characteristics, including well yields and water quality, have been summarized by Melvin (1985 p. 161-164). These aquifers, together with till and fine-grained stratified deposits of glaciolacustrine origin, are the major hydrogeologic units in the State. Hydraulic conductivities and storage properties of these units were compiled by Randall and others (1988, table 1) for the northeastern Appalachian region. Relevant data from this compilation and other comparable Connecticut data are listed in table 1.

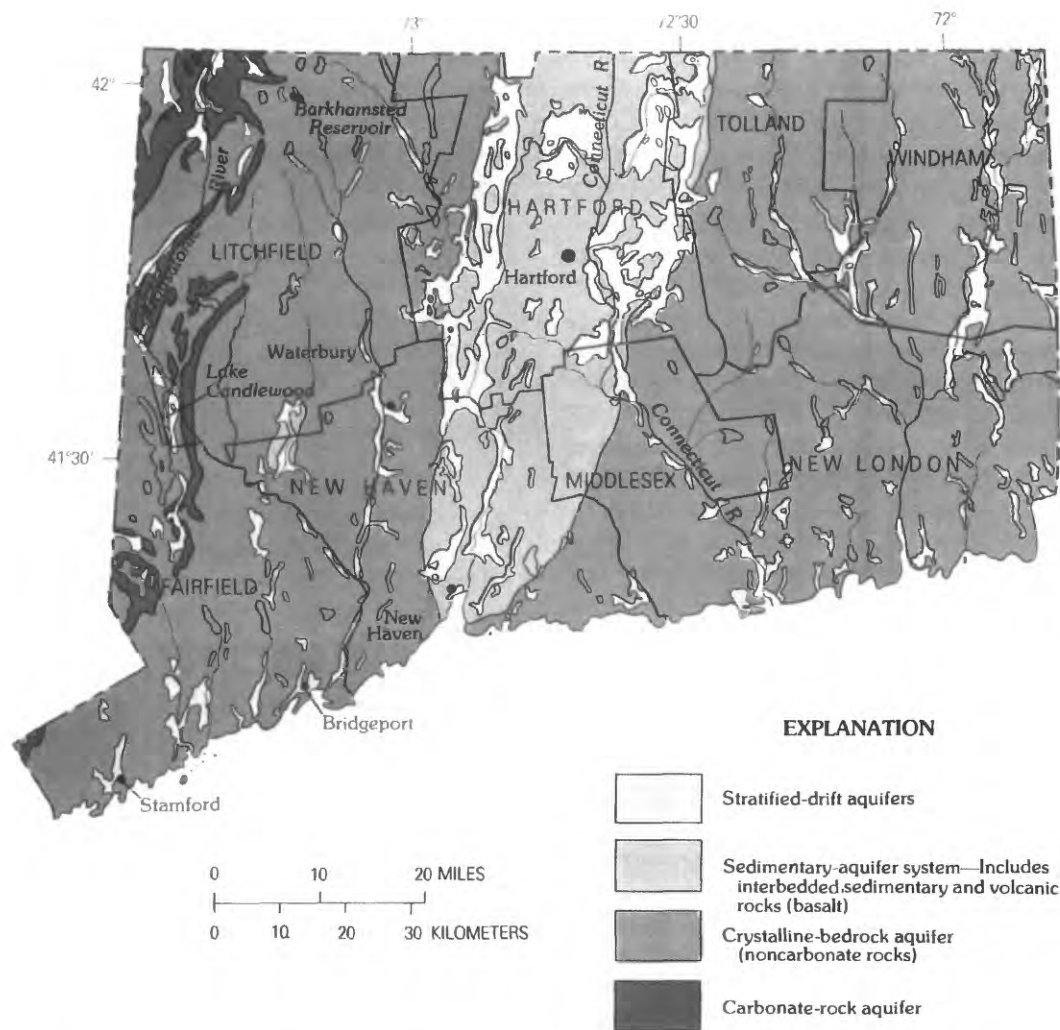


Figure 2.—Principal aquifers in Connecticut (From Melvin, 1985, fig. 1A).

Table 1.--Representative values of hydraulic properties of hydrogeologic units in Connecticut  
[ft, feet; ft/d, feet per day; ---, no data or insufficient data]

Unit and thickness	Median hydraulic conductivity <sup>1/</sup> (ft/d)	Median storativity <sup>2/</sup> (dimensionless)	Median intergranular porosity (percent)	Method or basis for computing median hydraulic conductivity, porosity, and storativity values	References
<u>Fractured bedrock</u>					
Crystalline bedrock top 30-330 ft	0.6	---	2	Specific capacity of 250 wells, adjusted to small drawdown; laboratory-determined porosity of 5 nonfractured core samples.	Randall and others (1966)
<u>Sedimentary bedrock,</u>					
top 100-500 ft	4.7	0.0003	---	Aquifer tests of 52 industrial/municipal wells.	Randall and others (1988)
top 30-650 ft	.31	---	---	Specific capacity of 401 wells, as reported by drillers.	Ryder and others (1981)
not subdivided	---	---	6	21 thin sections and 14 core samples, mainly arkose.	Heald (1956); Haeni and Anderson (1980)
Carbonate bedrock	---	---	---	---	---
<u>Stratified drift</u>					
Coarse-grained (sand and gravel), less than 100 ft	170	---	---	Aquifer tests or specific capacities adjusted for partial penetration for 157 screened wells; median aquifer thickness 56 ft.	Randall and others (1988)
	---	.36	---	25 undisturbed samples.	do
Fine-grained (fine sand, silt, and clay), 20-400 ft	.14	.29	---	6 undisturbed samples of lake silts, oriented vertically;	Randall and others (1966)
	.0001	---	---	3 undisturbed samples of varved clay, oriented vertically;	M.S. Klein, MRE, written commun. (1981)
	.82	---	---	3 undisturbed samples of varved clay, oriented horizontally.	do

Unit and thickness	Median hydraulic conductivity <sup>1/</sup> (ft/d)	Median storativity <sup>2/</sup> (dimensionless)	Median intergranular porosity (percent)	Method or basis for computing median hydraulic conductivity, porosity, and storativity values	References
<u>Till</u>					
Loose surface till (crystalline-rock provenance), 0-15 ft	2.7	.28	---	10 undisturbed samples.	Randall and others (1988)
Compact drumlin till (crystalline-rock provenance), 10-200 ft	.06	.04	---	4 undisturbed samples, oriented vertically.	Randall and others (1966)
Till, not subdivided (crystalline-rock provenance)	.6	---	35	Slug tests of 42 wells; 15 laboratory-determined values of total porosity.	Torak (1979); Pietras (1981)
Loose surface till (sedimentary-rock provenance), 0-15 ft	.71	---	32	6 undisturbed samples, 5 oriented horizontally, 1 vertically; 5 laboratory-determined values of total porosity.	Melvin and others (in press)
Compact surface till and drumlin till (sedimentary-rock provenance), 10-180 ft	.007 .003 ---	--- --- ---	--- --- 25	18 undisturbed samples, oriented horizontally; 34 undisturbed samples, oriented vertically; 51 laboratory-determined values of total porosity.	do

<sup>1/</sup> For well tests, transmissivity divided by distance penetrated into hydrostratigraphic unit; the resulting values assume the unit is an isotropic homogeneous medium hydraulically equivalent to the real unit, which is heterogeneous. In bedrock, flow may be limited to fractures or fracture zones that intersect a small percentage of borehole length, and transmissivity and hydraulic conductivity may only be representative of the fractures and not the rock matrix.

<sup>2/</sup> Specific yield for stratified drift and till.

## HYDROGEOLOGY OF THICK-TILL DEPOSITS IN CONNECTICUT

The tills in Connecticut vary in age, thickness, color, composition, and hydraulic properties. The physical characteristics of the tills are related to the composition of the underlying bedrock and surficial materials from which the tills were derived. At present, the distribution and character of various tills in Connecticut are known only generally (Stone and others, in press).

No detailed hydrogeologic investigations of till comparable to those that would be required as part of a low-level radioactive-waste disposal site characterization study have been conducted in Connecticut. Studies of till by geologists, hydrologists, and soil scientists (Newton, 1978; Torak, 1979; Pelletier, 1982; Smith, 1984) and the numerous observations and measurements made incidental to broader studies of geology, hydrology, and soils in southern New England provide insight on the range of hydrogeologic conditions that may be found in till deposits in Connecticut. Review of existing information shows that many aspects of till hydrogeology are either poorly defined or not defined, including the structural and sedimentological features in the deep parts of thick-till deposits, the hydrology of the unsaturated zone, temporal and spatial variability in recharge, head distribution and flow paths in the saturated zone, and the physical and chemical properties that control contaminant transport. The subsequent description and discussion of till hydrogeology, therefore, are expected to provide guidance on the scope and complexity of any future site-characterization studies.

### Lithostratigraphic Units

The tills in Connecticut are correlated with two late Pleistocene continental glaciations of the southern New England region (Schafer and Hartshorn, 1965; Stone and others, 1985; Stone and Borns, 1986, Stone, in Weddle and others, 1989). Presently, the tills of each glaciation are designated by informal stratigraphic names or by proposed formal names for local varieties of till. The informal terms "upper till" or "new till", and "lower till" or "old till" refer to the local stratigraphic superposition of the two tills of different glaciations, and to their chronostratigraphic relationship (Schafer and Hartshorn, 1965; Stone and others, 1985; Stone and Borns, 1986). The upper till, referred to descriptively in this report as the surface till, comprises relatively sandy tills at the land surface that form the till deposit of the late Wisconsin glaciation. The compact and weathered lower till, referred to in this report as the drumlin till, is preserved in the lower parts of drumlins and related areas of thick till in Connecticut. The drumlin till was deposited during the late Illinoian glaciation, based on regional correlations.

The two tills are not present in laterally extensive superposed sheet bodies in the region. Gray surface till overlies weathered drumlin till in relatively few exposures (Pessl and Schafer, 1968), but a thin, sandy and stony surface till that overlies a mixed-till zone containing dislocated, sheared, and brecciated angular fragments of the drumlin till within a sandy surface-till matrix is common. The mixed-till zone is thus part of the surface till, derived from glacial erosion and deposition of materials from the underlying drumlin till and from adjacent rock sources. The mixed-till zone overlies weathered drumlin till, which, in turn, overlies nonweathered drumlin till at depth. In all two-till exposures, the base of the mixed-till zone of the surface till truncates the weathered zone and the fissility and joints of the drumlin till. In the crests of some drumlins and other



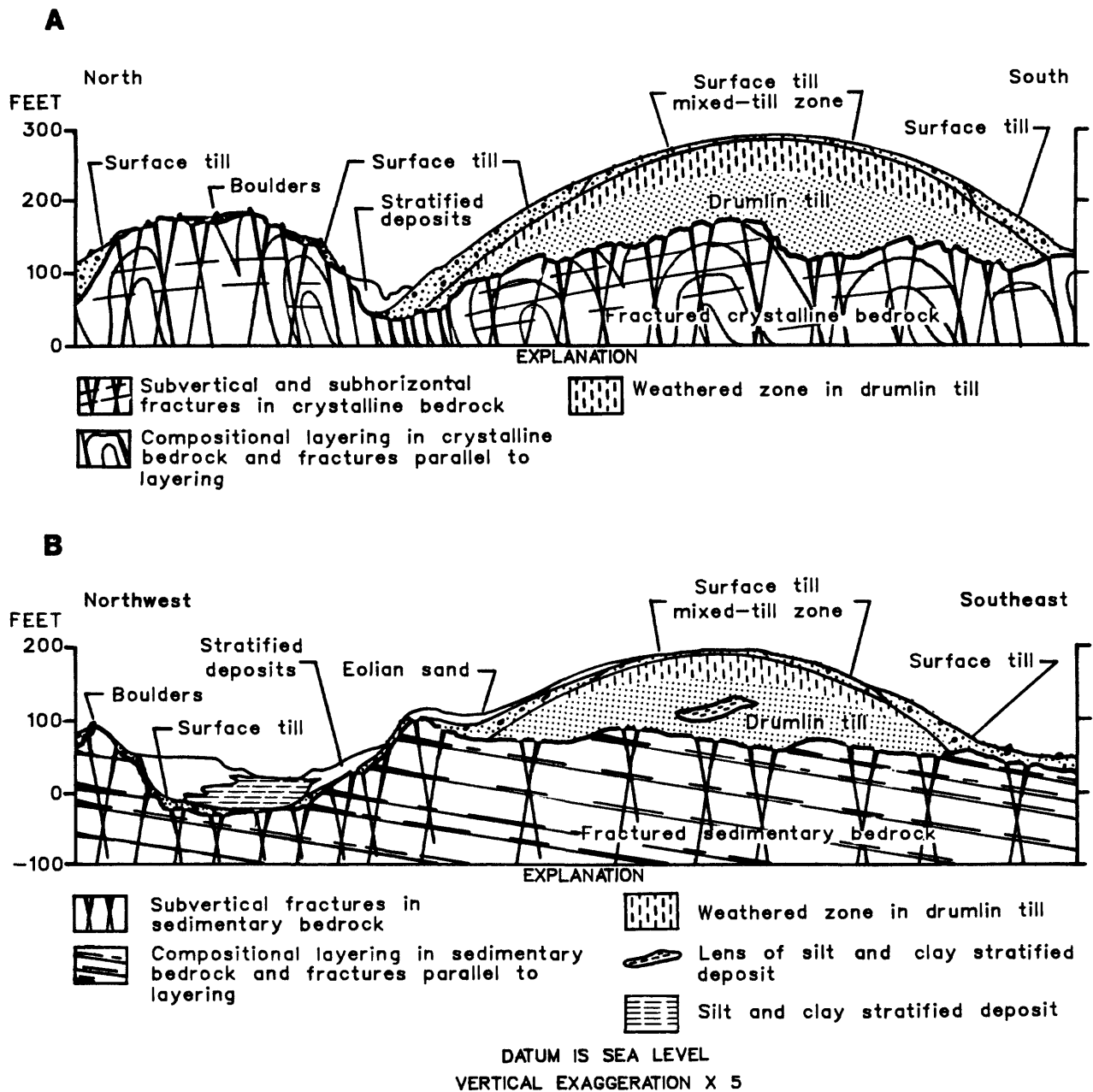


Figure 3.--Schematic distribution and relation of surface tills (late Wisconsinan), drumlin tills (Illinoian), weathered zones at top of drumlin tills, and mixed-till zones of the surface tills.

A. Tills overlying crystalline rocks in the western and eastern uplands.

B. Tills overlying sedimentary rock in the central lowland.

[Vertical scale shows altitude; horizontal scale is not specified, but the drumlin in figure 3A is about 4,500 feet (1,372 meters) long; vertical exaggeration in both figures is about 5. Based on numerous exposures and map data: Colton, 1965; Pessl and Schafer, 1968; Pease, 1970; Pessl, 1971; Stone, 1974; Thompson, 1975; Newton, 1978; Smith, 1984; London, 1985; Stone and others, 1985; modified from Stone, in Weddle and others, 1989; Melvin and others, in press.]

thick-till areas, typical surface till is not present and the mixed-till zone is at the land surface. In some other areas, the mixed-till zone may be absent or present only within the modern soil, and the weathered zone of the drumlin till is consequently at the land surface. The stratigraphic relationships of the surface and drumlin tills, the mixed-till zone, and the weathered zone in drumlin till are shown schematically in figure 3A and 3B.

### Distribution of Deposits

#### Surface (Upper) Till

The surface till forms an irregular blanket over bedrock uplands and beneath stratified deposits in valleys. It is highly variable in thickness, dependent in part on the composition and erodability of local bedrock and older surficial materials from which the till was derived. In areas of thin till that contain bedrock outcrops, the topography of the till surface is controlled by bedrock-surface relief (fig. 3). Here the till is discontinuous, probably averaging less than 6.5 ft (2 m) in thickness and contains numerous boulders. In other areas on northward-facing lower valley slopes, the till forms smooth-to-bumpy patches, 10 to 33 ft (3 to 10.1 m) thick. In these areas, the till is generally compact. A loose, sandy, and bouldery type of surface till forms a discontinuous, thin overlying unit in bedrock outcrop areas and areas of thicker till. Locally, and in end moraines, the loose till is thick enough to form hummocky surface topography. South of Hartford in the central lowland, compact till locally contains or overlies extensive deposits of stratified silt, clay, and sand (Simpson, 1959; Deane, 1967). The till surface is smooth and forms low elongate hills that are smaller than typical drumlin forms. The till in these areas is inferred to be chiefly surface till. Samples of this till were exceptionally clayey (Deane, 1967), evidence of the incorporation of underlying clay into the till. Similar surface till may underlie small drumlins in the southern part of the central lowland.

Local varieties of surface till are related closely in color, mineral composition, and grain size to local bedrock sources (Flint, 1930; Stone and others, 1985). Red to reddish-brown till derived from the sedimentary rocks of the central lowland (fig. 1) was deposited throughout the lowland, but only as far as 1 mi (1.6 km) east of the eastern border of Mesozoic rocks (Langer, 1977), and as far as 1.9 mi (3.0 km) west of the western border of the Mesozoic rocks (Flint, 1962). In the western and eastern uplands, local compositional varieties of the surface till similarly extend less than 2 mi (3.2 km) beyond the areas underlain by the source rocks (Stone and Force, 1983; Smith, 1984; Force and Stone, 1990).

#### Drumlin (Lower) Till

Drumlin till is preserved almost exclusively as a subsurface unit in drumlins and related bodies of glacially smoothed and streamlined thick till (fig. 3). A total of 1,573 drumlins have been identified within areas of thick till shown on the surficial materials map (Stone and others, in press; J.R. Stone and J.P. Schafer, U.S. Geological Survey, written commun., 1985). Exposures of drumlin till have been described throughout the State (White, 1947; Flint, 1961; Pessl, 1966; Pessl and Schafer, 1968; Pease, 1970; Stone, 1974; Thompson, 1975; Newton 1978; Smith, 1984). Drumlins in Connecticut are elongate hills with smooth surface topography, oval or elliptical in plan, and with their long axes oriented parallel to ice-movement directions.

They typically are 0.5 to 1 mi (0.8 to 1.6 km) long, 1,500 to 2,000 ft (460 to 610 m) wide, and 100 to 150 ft (30 to 46 m) high. Drumlin heights, measured from adjacent flat areas, vary from 35 to 150 ft (10.7 to 46 m). Some degree of asymmetry is universal, especially where areas of thick till extend down or along slopes adjacent to the drumlin.

Drumlins and related thick-till areas do not contain rock outcrops and do not have linear topographic elements that are parallel to the trend of underlying bedrock structures. Drumlins in Connecticut, identified by geologic interpretation of aerial photographs, field studies, and subsurface data that confirm their thick-till composition, thus do not include the rock-cored drumlins described by Flint (1930). It is inferred that thick drumlin-till deposits overlie bedrock hills that have relief similar to local relief in adjacent thin-till areas (fig. 3). Subsurface data indicate that some areas of thick till outside of drumlins contain drumlin till that is less than 30 ft (9.1 m) thick; locally in some of these areas, bedrock is within 10 ft (3 m) of the land surface (Pietras, 1981). The distribution of drumlins and related thick-till areas is related to the distribution of micaceous rocks, such as schists in crystalline-rock areas, and shale and arkosic sandstone in the central lowland (Flint, 1930; Stone and others, 1985). Drumlin till is inferred to be more than 30 ft (9.1 m) thick in all drumlins, and generally more than 100 ft (30 m) thick in drumlins that are more than 100 ft (30 m) in height. Till in a Connecticut drumlin has a maximum reported thickness of about 200 ft (61 m) (Stone and others, 1985).

#### Genesis and Age of Deposits

Genetic facies of the tills of the region are defined within the framework of an internationally recognized genetic classification of tills (International Union for Quaternary Research [INQUA] Commission on Genesis and Lithology of Quaternary Deposits, in Dreimanis, 1989). In Connecticut, areally extensive compact surface tills reported in mapping studies, hydrologic investigations, and topical research studies (Pessl, 1971; Newton, 1978; Smith, 1984) are subglacial (basal) lodgement till or subglacial meltout till of the genetic classification. The loose, sandy, bouldery facies of surface till (Pessl and Schafer, 1968; Pessl, 1971; Stone and others, 1985) is recognized genetically as a supraglacial meltout till (also known as ablation till, Pelletier, 1982). Minor flowtills and other poorly sorted sediments are interbedded in stratified deposits (Smith, 1984); genetically, these are supraglacial mass-movement tills. The compact drumlin till has been classified as a subglacial lodgement till (Pessl, 1971; Stone, 1974; Thompson, 1975; Smith, 1984) and locally as a subglacial meltout till (Newton, 1978). No supraglacial facies of the drumlin till are known to be present in Connecticut.

The surface till deposit has been dated in New England by radiocarbon dates from preglacial subglacial materials incorporated in the glacial sediments and from postglacial materials that overlie the sediments (Stone and Borns, 1986). It is the till deposit of the late Wisconsin glaciation, which occurred from about 23,000 BP (radiocarbon years before present) to deglaciation of the State about 16,000 BP (Stone and Borns, 1986).

The age of the drumlin till previously was known to be pre-late Wisconsinan (Schafer and Hartshorn, 1965). Consideration of radiocarbon-age constraints on the late Wisconsin glaciation, dated interglacial sediments on Long Island, and weathering characteristics of the drumlin till (Stone and Borns, 1986; Newman and others, 1990) has led to correlation of the drumlin till with the lower till at Sankaty Head in Nantucket, Massachusetts, inferred to be of Illinoian age (Oldale and others, 1982; Oldale and Colman, 1988). The drumlin till of Connecticut presently is correlated with the late Illinoian glaciation, which extended from about 180,000 to 150,000 BP (Richmond and Fullerton, 1986).

### Physical Characteristics of Deposits

Physical characteristics observed in the field are used to differentiate local varieties of the two tills in areas of similar bedrock type. Because of the close relation of till composition and texture to local bedrock source areas (provenance) (Flint, 1930; Langer, 1977; Smith, 1984; Stone and others, 1985; Force and Stone, 1990), differences in characteristics within one till unit may be greater than differences in characteristics between varieties of both units.

#### Surface (Upper) Till

##### Color and mineralogy

In areas of crystalline-rock provenance, the surface till is generally gray below the modern soil, reflecting the fresh, nonoxidized state of minerals in the till matrix. In areas of weathered sulfidic schists, the tills are rusty or yellowish brown, and in areas of other weathered or stained crystalline rocks, the tills are pale brown, resulting from incorporation of previously weathered rock materials. Marble rock units produce light-colored till; dark schists, phyllites, and mafic rocks produce dark-colored tills. Tills in the central lowland are red to reddish brown with variations to reddish gray, brown, or light brown. The till is grayish brown near basalt and diabase ridges.

The surface till contains locally derived gravel clasts (Goldsmith, 1982; Smith, 1984; Force and Stone, 1990). Detailed studies in western Connecticut (Smith, 1984) and eastern Connecticut (Stone and Force, 1983; Force and Stone, 1990) showed that sand-matrix mineralogy similarly is of local derivation, as shown by unique metamorphic indicator minerals from local rock units and by ratios of common constituents such as magnetite and ilmenite. Clay minerals in the upper tills are mainly illite and chlorite (Stone, 1974; Thompson, 1975; Newton, 1978; Smith, 1984). In the central lowland, illite, vermiculite, kaolinite, and a variety of interlayered minerals are present in rock units (April, 1978) and probably are in the till.

##### Grain size

Particle-size analysis of whole-till samples of surface till, including visual estimates of volumetric stone content (Stone, in Weddle and others, 1989), shows that the proportion of gravel is greater than 30 percent (also see Pessl and Schafer, 1968; Melvin and others, in press). The stoniness (large pebbles to large boulders) of the compact surface till is 5 to 30 percent by weight. Boulders 3 to 6 ft (0.91 to 1.8 m) in length commonly are found in large excavations of compact surface till. The proportion of sand varies greatly within the compact facies of the surface till (fig. 4A and 4B). This variation is related chiefly to the grain size of the local

bedrock and surficial-material sources of the till and, to a minor degree, to glacial pulverization of the rock fragments (Stone and Force, 1983; Smith, 1984, 1989; Force and Stone, 1990). Sandy surface tills derived from crystalline rocks contain as much as 91-percent sand, and 9- to 64-percent silt and clay, whereas surface tills derived from marble and schist in western Connecticut are notably siltier, containing as much as 66-percent silt. Compact surface till derived from crystalline rocks generally contains less than 6-percent clay, but where the tills are derived from marble and schist, they contain as much as 20-percent clay (fig. 4A). The grain size of surface tills in the central lowland is highly variable, ranging from sandy (80-percent sand) to silty and clayey (78-percent silt and clay) (fig. 4B). Clayey tills occur in some areas where there were fine-grained source materials. Deane (1967) described clayey tills in the Hartford area derived in part from older lacustrine deposits. Samples of these tills contain more than 30-percent clay, as shown in figure 4B.

### Geotechnical classification

Geotechnical properties of the surface tills that are related to flow of water through the tills and to construction performance are dependent on the grain-size and plasticity-index properties of these sandy materials. In the Unified Soils Classification of engineering soils (American Society for Testing Materials, 1990), the compact surface tills are classified as silty sand with gravel with 3- to 17-percent cobbles and boulders by volume (soil type SM), or poorly graded sand with silt and with gravel and with 3- to 17- percent cobbles and boulders by volume (soil type SP-SM). Samples of the fine fraction of surface-till matrix (grain size less than 0.017 in. (0.42 mm) diameter) reportedly are nonplastic (Ilgen and others, 1966).

### Layering, fabric, and structure

Textural layering is common in the upper part of deep exposures of the surface till. The layering consists of subhorizontal thin beds or laminae of lighter colored, sandy layers interbedded with darker, finer-grained, and more compact layers. In exposures of the supraglacial meltout facies, layered sandy materials contain lenses of thinly bedded and laminated fine-to-coarse sand, silt, and minor gravel or clay. The lenses generally are less than 3 ft (1 m) thick, and are laterally continuous over distances of several feet (Pessl, 1971; Smith, 1984). In the compact subglacial facies, subhorizontal fissility (closely spaced planar fractures) is weakly developed and is probably related to the preferred orientation of particles in the till matrix (Pessl and Schafer, 1968; Stone, 1974). Elongate sand grains have a preferred orientation parallel to the direction of glacier flow, and elongate stones have preferred orientation of long axes in the direction of glacier flow (Pessl, 1971; Newton, 1978).

### Weathering and soils

Soils developed in the surface till and overlying eolian (wind-blown) materials (Ritchie and others, 1957; Pelletier, 1982) during the last 16,000 years since late-Wisconsin deglaciation are inceptisols, with solum thickness (total thickness of A and B horizons) of 18 to 36 in. (45 to 91 cm). The soils are characterized by cambic B-horizons, which contain less than 20 percent more clay than overlying horizons, have weak to moderate development of soil structure, and weakly modified clay mineralogy.

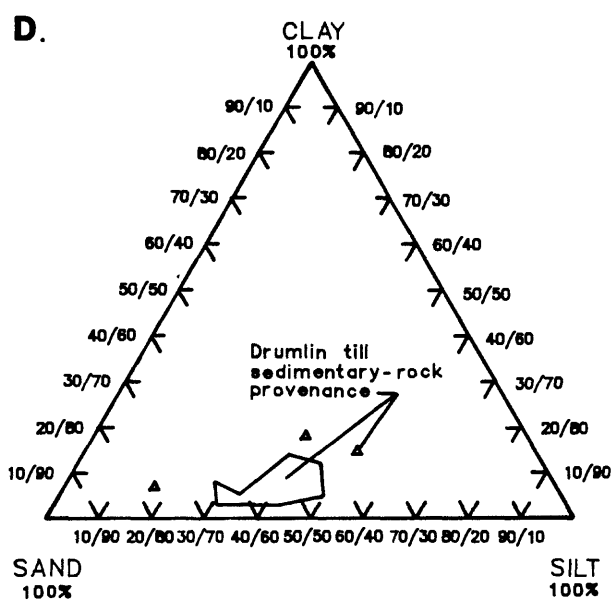
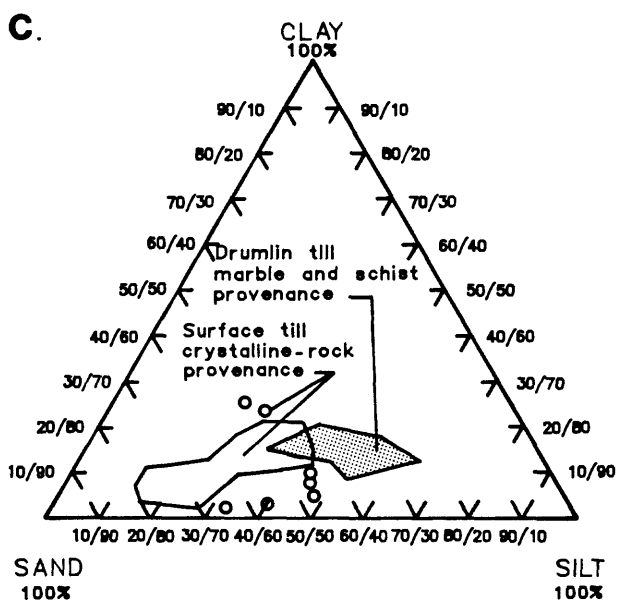
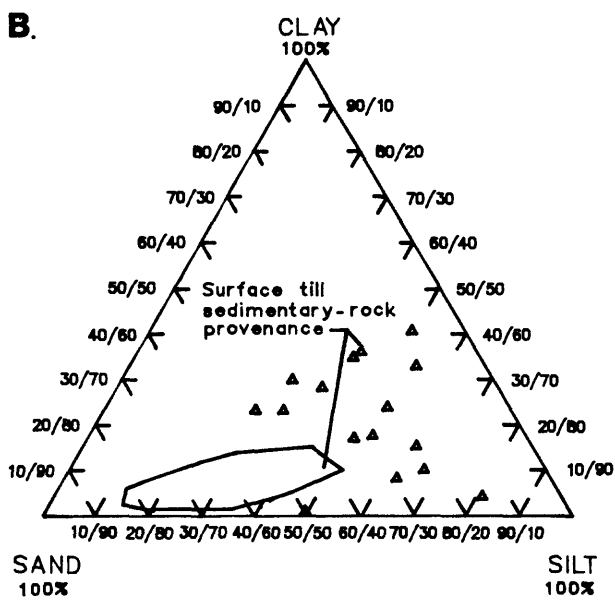
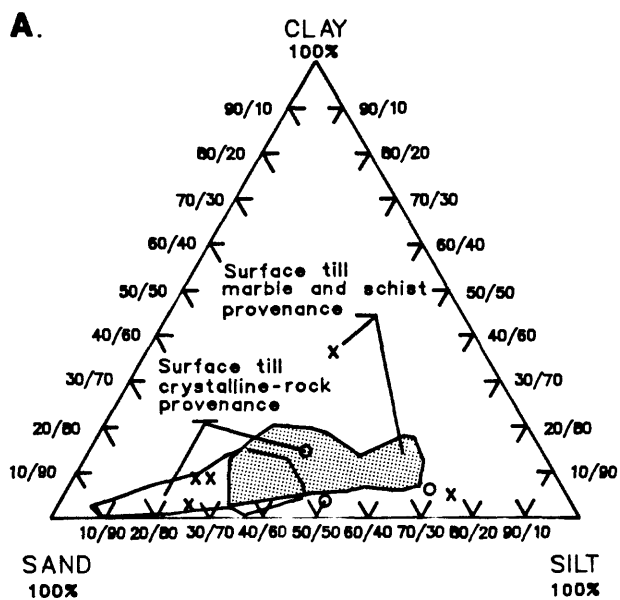


Figure 4.--Ternary diagrams showing sand-silt-clay content of the matrix of surface and drumlin tills in Connecticut.

A. Compact surface tills of crystalline-rock provenance (excluding marble and schist) from the western and eastern uplands (128 values used; field contains 125 values, 3 outlying values), and compact surface tills of marble and schist provenance from western Connecticut (121 values used; field contains 116 values, 5 outlying values). Data from Pessl and Schafer, 1968; Stone, 1974; Thompson, 1975; Pelletier, 1982; Smith, 1984; Mullaney and others, in press.

B. Compact surface tills of sedimentary-rock provenance from the central lowland (61 values used; field contains 45 values, 16 outlying values). Clayey tills of Deane (1967) (9 outlying values and more than 20-percent clay) are inferred to be late Wisconsinan in age; some of these tills may be flowtills. Data from Colton, 1960; Deane, 1967; Soil Conservation Service, written commun., 1986; U.S. Geological Survey, written commun., 1991; Mullaney and others, in press.

C. Drumlin tills of crystalline-rock provenance (excluding marble and schist) from the western and eastern uplands (100 values used; field contains 93 values, 7 outlying values), and drumlin tills of marble and schist provenance from western Connecticut (field contains 29 values). Data from Linell and Shea, 1961; Pessl and Schafer, 1968; Stone, 1974; Newton, 1978; Thompson, 1975; Pelletier, 1982; Smith, 1984.

D. Drumlin tills of sedimentary-rock provenance from the central lowland (16 values used; field contains 13 values, 3 outlying values). Some samples may include mixed surface- and drumlin-till materials from the mixed-till zone. Data from Bourbeau and Swanson, 1954; U.S. Geological Survey, written commun., 1991; Mullaney and others, in press.

[Sand particle size, 0.08 to 0.02 inches (2.0 to 0.05 millimeters); silt particle size, 0.02 to 0.0008 inches (0.05 to 0.002 millimeters); clay particle size, less than 0.0008 inches (0.002 millimeters). Grain-size classification from U.S. Department of Agriculture (1975)]

Typical soil series in crystalline-rock uplands of Connecticut are the Montauk, Charlton, and Leicester series (in continuous till on lower slopes (Crouch, 1980; Wolf, 1981)); the Hollis series (in thin till in areas of rock outcrop, with solum 10 to 20 in. (25 to 50 cm) thick over bedrock (Wolf, 1981)); and the Canton and Gloucester series (in sandy and stony supraglacial meltout till (Roberts, 1981) and the "ablation till" (Pelletier, 1982)). The Stockbridge, Georgia, and Nellis series are developed in areas of calcareous tills derived from marble in western Connecticut (Gonick and others, 1970). Reddish-brown soils in the central lowland are the Cheshire and Yalesville series (in continuous till or in areas of sedimentary rock outcrop (Reynolds, 1979a,b)), and the Narragansett series (in thick eolian silt on top of red till (Tamura and others, 1957; Ritchie and others, 1957; Shearin and Hill, 1962)).

Soils developed in the mixed-till zone at the surface of some drumlins in the uplands are the Paxton (well-drained, at tops of hills), Woodbridge, and Ridgebury series (Wolf, 1981; Roberts, 1981); solum thickness is 10 to 30 in. (25 to 76 cm). The solum overlies the C horizon that commonly is in the mixed-till zone. In some drumlins having very thin mixed-till zones at the surface, the modern solum is developed in an older weathered zone in the drumlin till that is oxidized as deep as 37 ft (11.3 m). Soils developed in mixed-till zones in drumlins in the central lowland are the Wethersfield (well-drained, at tops of hills), Ludlow, and Wilbraham series (Reynolds, 1979a). The solum thickness of these soils is 16 to 36 in. (40 to 91 cm). The solum overlies the C horizon, which is in the mixed-till zone or in weathered drumlin till.

#### Drumlin (Lower) Till

##### Color and mineralogy

In areas of crystalline-rock provenance, the color of nonweathered drumlin till commonly is dark gray, reported locally as blue-gray. The olive color of the drumlin till in the weathered zone is due to a pervasive oxidation stain of the matrix (discussed below). In the central lowland, the drumlin till is generally reddish brown to brownish red. It is difficult to distinguish the drumlin till from compact red surface till in the central lowland, but it has been recognized in many drumlins on the basis of fissility and joint structures, iron-manganese stain on deep joints, and relative degree of compaction and low water content (J.P. Schafer, U.S. Geological Survey, written commun., 1985).

The till contains locally derived gravel clasts (Smith, 1984). Sand mineralogy is similarly of local derivation, as shown by unique metamorphic minerals and by ratios of common constituents, such as magnetite and ilmenite. Clay minerals in the drumlin till are illite and chlorite, and in the weathered zone, the clay minerals include illite-vermiculite phases (Stone, 1974; Thompson, 1975; Newton, 1978; Smith, 1984).

##### Grain size

Particle-size analysis of whole till samples of drumlin till (Stone in Weddle and others, 1989) shows that the proportion of gravel is commonly less than 25 percent. The stoniness (pebbles to boulders) of the drumlin till is less than 10 percent. Boulders more than 3 ft (1 m) in length are notably rare in large excavations of drumlin till. In the till matrix, the proportion of sand varies among varieties of the drumlin till (fig. 4C).



This variation is related chiefly to the grain size of the local bedrock and surficial materials from which the till was derived. Samples from many shallow exposures and a few deep exposures across the State have an average sand content of 57 percent. Drumlin till derived from coarse-grained crystalline rocks contains 33- to 58-percent silt and clay, but where the till was derived from schist and marble, it contains more than 50-percent combined silt and clay, and as much as 77-percent silt and clay. The drumlin tills of crystalline-rock provenance generally contain more than 10-percent clay, and as much as 25 percent. The clay fraction contains a measurable amount of fine clay (particle diameter less than 0.00008 in. (0.002 mm)) (Stone, 1974). The texture of drumlin till in the central lowland is silty to clayey silt. Samples from three sites in figure 4D are from shallow exposures or from a thick-till deposit that contains sorted sand below the till (Melvin and others, in press). These tills probably contain an unusually large proportion of sand; they all contain more than 3-percent clay.

### Geotechnical classification

The drumlin till is characterized by low permeability and high shear strength, which make it an ideal material for construction of earthen dams (Linell and Shea, 1961). These properties, in turn, depend on the grain-size and plasticity-index characteristics of this silty sand material. Reported variations in the texture of drumlin till have led to a four-fold classification in the Unified Soils Classification of engineering soils (American Society of Testing Materials, 1990): (1) clayey sand with gravel, with 1- to 15-percent cobbles and boulders by volume (soil type SC); (2 and 3) silty sand with gravel, with 1- to 15-percent cobbles and boulders by volume (soil types SM, SC-SM); and (4) sandy silt with gravel and with 1- to 15-percent cobbles and boulders by volume (soil type ML). Samples of the fine fraction of drumlin-till matrix (grain size less than 0.017 in. (0.42 mm diameter)) reportedly have plasticity index values of 5 to 18.2 (range of water content in percent) (Linell and Shea, 1961; Reynolds, 1979a; Roberts, 1981).

### Layering, fabric, and structure

Drumlin till exposed in deep excavations appears massive; however, thin veins of clay or fine sand (Newton, 1978) extend through the matrix a few inches to a few feet. Textural layering, consisting of subhorizontal thin beds or laminae of lighter colored, sandy layers, is rare. However, fine sand is present in sheared zones in the upper parts of some exposures (Pessl and Schafer, 1968). Newton (1978) also described a 5.9-in. (15-cm) wide clastic dike filled with gravel and sand. In the central lowland, masses of silt and clay, sand, and gravel have been described in the cores of two drumlins (Colton, 1965; London, 1985). The 133-ft (40-m) thick sequence of stratified clay, fine sand, and sand and gravel described from a borehole by Colton (1965), and similar sediments described by London are overlain by compact, silty reddish-brown till, which is inferred to be drumlin till. Cores from another thick drumlin till deposit (U.S. Geological Survey, written commun., 1991), indicate that the stratified materials occur as discontinuous lenses within the till. Elongate stones in drumlin till have preferred orientation of their long axes in the direction of glacier flow (Pessl, 1971; Smith, 1984), but sand grains do not have a strong preferred orientation (Newton, 1978). Platy minerals display only a weak preferred alignment in thin sections (Stone, 1974). Subhorizontal fissility is well developed in the weathered zone of the till, but is more widely spaced and weakly developed at depth. The fissility is not apparent in lower parts of deep exposures, but dried samples of the till part along subhorizontal surfaces of fissility.

## Weathered zone

The weathered zone at the top of nearly all drumlin-till exposures is 10 ft (3 m) to as much as 37 ft (11.3 m) thick. It is developed in the drumlin till, below the mixed-till zone and the modern soil. The base of the oxidized zone is subparallel to the surface of the landform, indicating weathering after glacial smoothing (fig. 3A, 3B). Weathering effects are progressive upward through the zone; pH values decline (Stone, 1974), amount of leaching increases (Thompson, 1975), color values of matrix stain increase (Pessl and Schafer, 1968), degree and darkness of iron and manganese stain on joint faces increase, and blocky structure increases and is more densely developed (Pessl and Schafer, 1968). The upwardly progressive hydration of altered illite in the weathered zone (Stone, 1974) is characterized as alteration of illite to vermiculite and mixed-layer illite-vermiculite (Newton, 1978, 1979b). Oxidation of iron-bearing minerals has resulted in staining of the till matrix (Stone, 1974), and surfaces of oxidized garnet grains are pitted (Newton, 1978). In drumlin till that contains chlorite in the clay fraction, alteration of chlorite to vermiculite also increases upward through the oxidized zone (Quigley and Martin, 1967; Thompson, 1975; Newman and others, 1990). In the red to reddish-brown till of the central lowland, the weathered zone in the drumlin till is desiccated and contains clay coatings and iron-manganese coatings on joints as deep as 25 ft (7.6 m) (J.P. Schafer, U.S. Geological Survey, written commun., 1985). The weathered zone of the drumlin tills is the upper part of the C-horizon of a probable well-developed interglacial soil (Pessl and Schafer, 1968; Stone, 1974; Thompson, 1975; Newton, 1978), the solum of which was removed by late Wisconsin glacial erosion.

## Ground-Water Recharge, Discharge, and Circulation in Till Areas

Infiltration of precipitation, percolation to the saturated zone (recharge), circulation of ground water, and discharge from the saturated zone in till areas can be described only qualitatively. The high infiltration rates and hydraulic conductivities commonly reported for the soil developed on till relative to the till substratum (Reynolds, 1979b; Pietras, 1981; Pelletier, 1982; Welling, 1983), and the general absence of well-developed stream channels indicate that most precipitation in thick-till areas is able to infiltrate the land surface. The amount of water infiltrating the land surface and the amount that eventually reaches the saturated zone vary spatially and temporally in response to climatic, topographic, and biologic factors and are influenced by local differences in infiltration capacity and hydraulic properties of the materials in the unsaturated zone.

The percolation of water through the unsaturated zone to the water table in recharge areas has not been directly measured in till-covered areas in Connecticut. Randall and others (1966, p. 63-66) and Thomas and others (1967, p. 65-67) developed estimates of recharge in areas of till-mantled bedrock in eastern Connecticut. These estimates were developed from hydrologic budgets for three small till-covered basins. The budgets were computed for 1-year periods over which there was no change in storage. Ground-water recharge was considered equal to ground-water discharge (ground-water runoff plus any underflow) and ranged from 5.71 to 8.16 in. (14.5 to 20.7 cm). The estimates do not account for any areal variations in recharge within the basins, may pertain to both the till and underlying crystalline bedrock, and neglect ground-water evapotranspiration, which may be a major component of ground-water discharge (Meinzer and Stearns, 1929).

These factors, together with the short duration of the hydrologic budget analyses and the low precipitation in eastern Connecticut during the periods of analyses (Hunter and Meade, 1983) indicate these estimates are conservative and limit their usefulness.

The relation between recharge rates and disposal of low-level radioactive wastes above the water table are discussed by Ichimura (1990). He concluded from a simplified theoretical analysis that burial of low-level radioactive waste above the water table poses problems in porous media with minimal permeability and specific yield when net recharge rates exceed about 1 in/yr (2.5 cm/year) (Ichimura, 1990, p. 103). The problems arise because of the shallow depth to the water table and rapid rises in the water table resulting from recharge.

The general configuration of the water table and circulation within the saturated zone in thick-till areas appears to conform to what is typical in a humid area of moderate topographic relief (Randall and others, 1988, fig. 1). (See figure 5.) Topographically high areas, such as hilltops and upper slopes, are recharge areas where vertical gradients are downward (Pietras, 1981, table 11). The bedrock in this setting is generally within 100 ft (30 m) of the water table. Unpublished USGS data from New Hampshire show that the downward vertical gradients can extend into the bedrock in areas underlain by till that is as much as 132 ft (40 m) thick (P.T. Harte, U.S. Geological Survey, written commun., 1991). Discharge occurs largely as ground-water runoff to streams and swamps in the topographically low areas adjacent to till-covered hillsides, and by evapotranspiration of ground water where the water table or capillary fringe are near the land surface. Upward vertical hydraulic gradients have been measured by Pietras (1981) and Mullaney and others (in press) beneath the lower slopes of hillsides, indicating that these lower slopes may also represent discharge areas, particularly if the bedrock is shallow. It might be expected that the water table would be shallower on the lower slopes of features such as drumlins than near the hilltop. However, water levels measured in wells on a drumlin near New Haven (Brown, 1928, p. 26-27) show that this is not always the case and that the depth to water can be greater on lower slopes than near the top of the drumlin.

The lengths of flow paths through the saturated zone (below the water table) have not been determined for any till areas in Connecticut. The shape of the water table in most areas is believed to be similar to that of the topography as shown in figure 5. Flow paths along the water table from topographically high recharge areas to discharge sites, estimated from examining topography and hydrography in representative areas of thick till (principally drumlin areas in northeastern, central, and west-central Connecticut), range from a few hundred to about 2,500 ft (762 m). Lengths of flow paths within the saturated zone from points of recharge to points of discharge may be slightly greater. The presence of intermittent streams noted by Pietras (1981, p. 100) and springs in small depressions on till hillsides noted by Brown (1928, pl. 14) indicate that small, transient flow systems may occur within larger flow systems in a till area. These small local flow systems are more likely during wet periods when the water table is high and flow paths within such systems could be as little as a few feet to a few tens of feet.

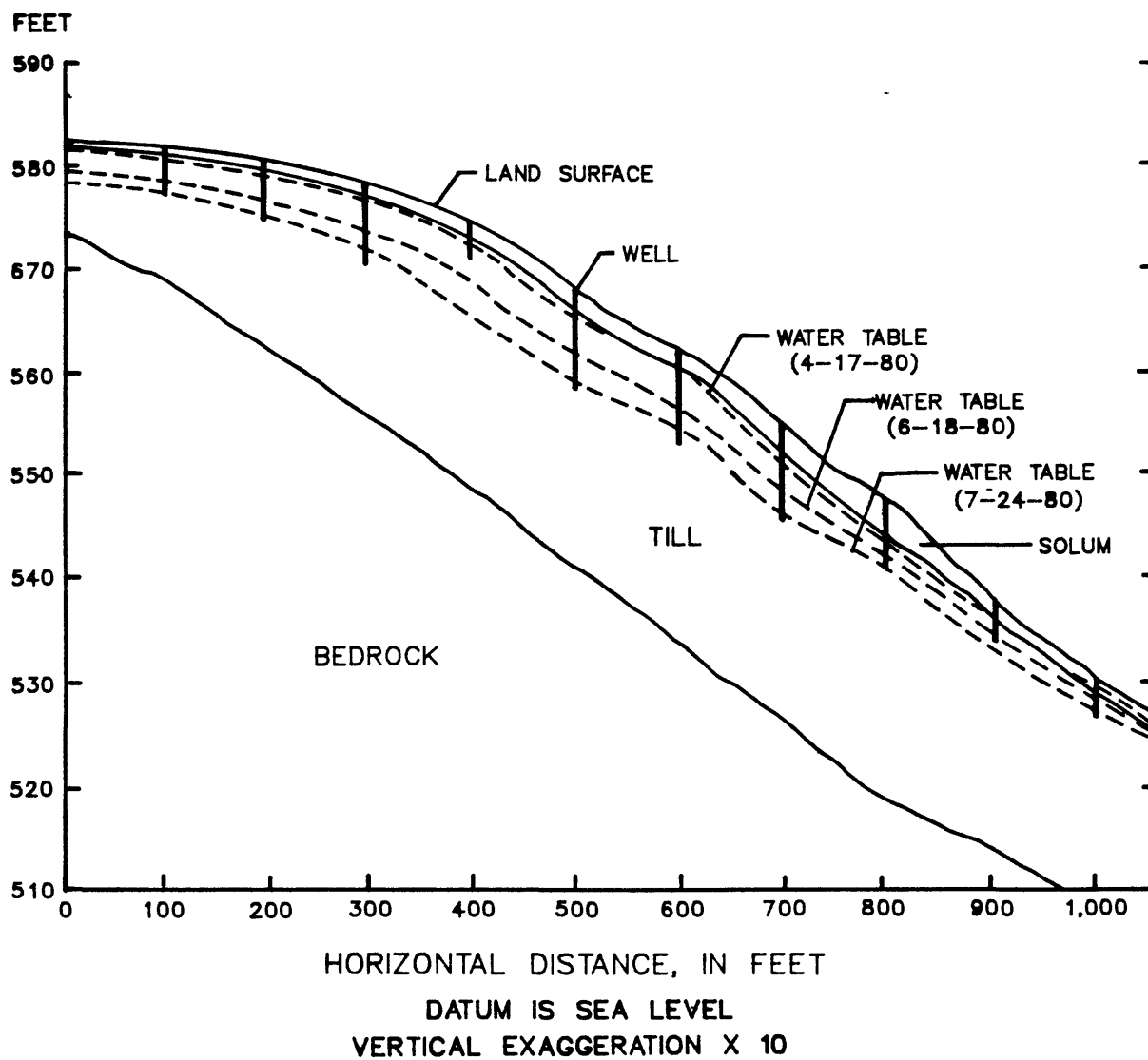


Figure 5.--Water-table configuration in a thick-till hillside in eastern Connecticut (from Pietras, 1981, fig. 10).

### Position of the Water Table

The position of the water table relative to the land surface is an important factor in selecting and characterizing a low-level radioactive-waste disposal site in Connecticut (Connecticut Hazardous Waste Management Service, 1990). The average depth to the water table is generally 10 to 15 ft (3 to 4.6 m) in the till deposits in Connecticut, based on several hundred measurements of water levels in dug wells made during early hydrogeologic studies (Gregory, 1909; Waring, 1920; Palmer, 1920, 1921; Brown, 1928). The water levels measured in 117 till wells within 75 mi (121 km) of Hartford were obtained from the U.S. Geological Survey's computerized Ground-Water-Site-Inventory data base. These measurements show a median depth to the water table of 11 ft (3.4 m). The water table ranged from land surface to 44 ft (13.4 m) below land surface, with half the measurements between 6.8 and 16 ft (2.1 to 4.9 m) below land surface. Pietras (1981, p. 100) has described the presence of transient perched water tables at one till site in eastern Connecticut and such conditions may occur in other areas if layers or lenses of material with low hydraulic conductivity are present within the unsaturated zone.

The depth to the water table can differ considerably from one place to another and with time. In early studies (Gregory, 1909; Waring, 1920; Palmer, 1920, 1921; Brown, 1928), measured depths ranged from about 2 ft (0.61 m) below land surface to somewhere between 20 to 40 ft (6.1 to 12.2 m) below land surface. Depths to the water table greater than 40 ft (12.2 m), have been reported (Gregory, 1909, p. 149; Palmer, 1921, p. 154; Thomas and others, 1966, p. 38), but such conditions are rare and probably occur in areas of very permeable till.

Changes in the position of the water table over time reflect changes in the balance between ground-water recharge and discharge. The magnitude of water-table fluctuation also may reflect local differences in topographic and geologic conditions. For example, the range in fluctuation may be smaller near discharge areas where the water table is high and only a limited quantity of recharge can be accepted before the water table or capillary fringe reaches land surface. Figure 6 summarizes a 45-year record of average monthly water-level changes in a well in Middlefield, Connecticut that penetrates till. During this period, the water table has ranged from 2.48 to 16.92 ft (0.76 to 5.2 m) below land surface. Records of eight other long-term USGS observation wells in till are summarized in table 2. These long-term records show that the water table can frequently be within 5 ft (1.5 m) of the land surface at many sites.

Table 2.--Long-term observations of water levels in selected Connecticut wells in till

[>, greater than]

Well number	Town	Period of record	Maximum (feet below land surface)	Minimum (feet below land surface)	Range (feet)
GO 14	Goshen	1958-1962	11.57	3.68	7.89
GR 328	Granby	1981-1991	17.44	4.49	12.95
GR 329	Granby	1982-1991	13.13	.92	12.21
MS 44	Mansfield	1982-1991	9.78	.13	9.65
SI 122	Simsbury	1953-1963	16.49	4.35	12.14
U 3	Union	1949-1964	>26	9.34	>16.66
WB 176	Waterbury	1944-1963	>16	2.65	>13.35
WB 198	Waterbury	1944-1991	21.76	5.49	16.27

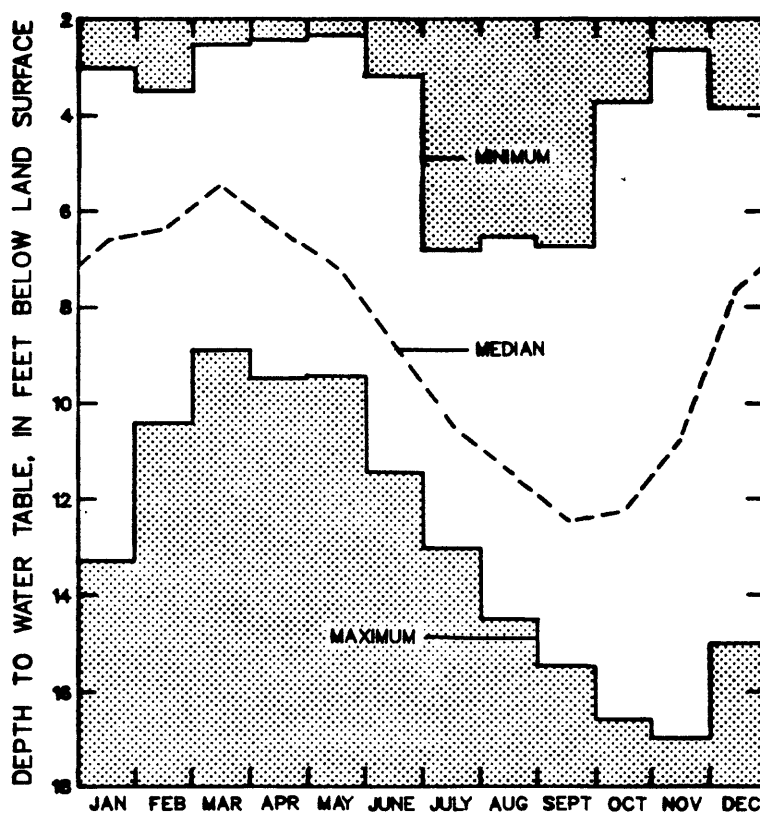


Figure 6.--Average monthly maximum and minimum water levels and median water levels, in U. S. Geological Survey observation well MF-1, July 1946 to November 1991.

The median monthly water levels in figure 6 show the typical annual pattern that reflects seasonal changes in the balance between recharge and discharge. In Connecticut, recharge generally exceeds discharge during the nongrowing season and is less than discharge during the growing season. The water table in most places is, therefore, generally highest in late winter and early spring following snowmelt and is lowest at the end of the growing season in late summer and early fall. During this annual cycle, fluctuations greater than shown by records of long-term observation wells have been noted. For example, the water level in well NSN 25 which penetrates thick till in southeastern Connecticut declined about 21 ft (6.4 m) in a 7-month period and subsequently rose 18 ft (5.5 m) in the following 3 months (Thomas and others, 1968, fig. 38).

It should be noted that the longest continuous USGS record of water-table changes in Connecticut till is 48 years (well WB 198 in table 2). The fluctuations in water-table position over much longer time spans (100 to 500 years) are unknown. Furthermore, the small intergranular pores in till favor a thick capillary fringe immediately above the water table, which is not reflected in any of the water-level data described herein. The thickness of this fringe is difficult to determine because water does not flow from it into a well. The capillary fringe, also termed the tension-saturated zone (Freeze and Cherry, 1979, p. 44), may have an active role in ground-water movement and contaminant transport in fine-grained till.

## Hydraulic Properties of Deposits

Knowledge about the hydraulic properties that control ground-water flow and transport of contaminants in Connecticut till is limited. Measurements of saturated hydraulic conductivity, total porosity, and specific yield from several sites in Connecticut and adjacent parts of southern New England have recently been compiled by Melvin and others (in press). The hydraulic-conductivity data are considerably more numerous than data on porosity and specific yield and no data on other properties needed to predict migration of contaminants, such as dispersivity of till, are reported in this compilation.

The horizontal hydraulic conductivities for surface and drumlin tills in southern New England that are derived from crystalline rocks, as determined by field (in-situ) tests and laboratory tests on undisturbed samples, range from  $2.8 \times 10^{-3}$  to 65 ft/d ( $1.0 \times 10^{-6}$  to  $2.3 \times 10^{-2}$  cm/s) and the vertical hydraulic conductivities of similar tills range from  $1.3 \times 10^{-2}$  to 96 ft/d ( $4.7 \times 10^{-6}$  to  $3.4 \times 10^{-2}$  cm/s). The comparable horizontal hydraulic conductivities for surface and drumlin tills derived from sedimentary rocks range from  $7.9 \times 10^{-4}$  to 3.4 ft/d ( $2.8 \times 10^{-7}$  to  $1.2 \times 10^{-3}$  cm/s) while the vertical hydraulic conductivities of similar tills range  $5.1 \times 10^{-4}$  to 3.4 ft/d ( $1.8 \times 10^{-7}$  to  $1.2 \times 10^{-3}$  cm/s) (Melvin and others, in press, table 3). These broad ranges (as much as four orders of magnitude) in hydraulic conductivity do not distinguish between surface till and drumlin till or the different facies of surface till, although most values appear to represent lodgement till. (See Melvin and others, in press, table 3.)

The adequacy of these data for characterizing the 'bulk' hydraulic conductivity and porosity of the bulk mass of till is not known. Several investigators, cited in Stephenson and others (1988, table 3), have noted that field-determined values of hydraulic conductivity for till are commonly at least one order of magnitude greater than laboratory-determined values for the same material. This discrepancy is ascribed to the till having both primary (intergranular or matrix) hydraulic conductivity and secondary hydraulic conductivity produced by fracturing or weathering. Only the primary hydraulic conductivity is measured by the laboratory tests, whereas the greater hydraulic conductivity due to secondary features, such as fractures, can be measured only by the field tests. There is also some question as to whether field-determined values of hydraulic conductivity resulting from conventional single-well response (slug) tests accurately characterize the bulk hydraulic conductivity of fractured till (D'Astous and others, 1989; Keller and others, 1989). This is because the wells in which the tests are conducted may not intersect vertical fractures and because fractures can be clogged by various drilling methods. The laboratory-determined values of hydraulic conductivity and porosity discussed in this report should be considered as representative only of the till matrix. The field-determined or in-situ values may be considered measures of the bulk properties, but their reliability in representing bulk properties at any site cannot be determined because of uncertainties about the methods used to collect and analyze field data. Such critical evaluation of reported data is beyond the scope of this report.

The most consistent hydraulic conductivity data for Connecticut tills derived from crystalline rocks, in respect to sampling and analytical methods, are from slug tests conducted in eastern Connecticut by Torak (1979) and Pietras (1981). (See Melvin and others, in press, table 3, sites 58-59, 61-64, 66-67, 73, 76-77, and 85.) The wells at these test sites penetrate surface till that may also contain the mixed-till zone and (or) drumlin till. Forty of the 44 values of horizontal hydraulic conductivity determined from these tests are in the range of  $4 \times 10^{-2}$  to 24 ft/d ( $1.4 \times 10^{-5}$  to  $8.5 \times 10^{-3}$  cm/s). Seven laboratory-determined hydraulic conductivity values reported by the USGS (Melvin and others, in press, table 3, sites 74, and 78-83) for samples of surface and drumlin till in eastern Connecticut extend over a comparable range, although six are vertical values. Both the slug-test and laboratory-determined values of hydraulic conductivity are at the upper end of the ranges commonly cited for tills (Freeze and Cherry, 1979, table 2.2; Stephenson and others, 1988, table 2).

The most consistent hydraulic conductivity data for Connecticut tills derived from Mesozoic sedimentary rocks are 58 laboratory-determined values for horizontally and vertically oriented core samples collected by the USGS from sites in central and north-central Connecticut (Melvin and others, in press, table 3, sites 10-11, 16, and 18-20). The 17 values of horizontal conductivity for compact drumlin till ranged from  $7.9 \times 10^{-4}$  to  $2.8 \times 10^{-1}$  ft/d ( $2.8 \times 10^{-7}$  to  $1 \times 10^{-4}$  cm/s); 15 of these values ranged from  $1.7 \times 10^{-3}$  ft/d to  $4 \times 10^{-2}$  ( $6.0 \times 10^{-7}$  to  $1.4 \times 10^{-5}$  cm/s). Vertical hydraulic conductivities for 32 samples of drumlin till were similar--they ranged from  $5.1 \times 10^{-4}$  to 1.5 ft/d ( $1.8 \times 10^{-7}$  to  $5.4 \times 10^{-4}$  cm/s); 25 of the values ranged from  $1 \times 10^{-3}$  to  $6.2 \times 10^{-2}$  ft/d ( $3.7 \times 10^{-7}$  to  $2.3 \times 10^{-5}$  cm/s). These values are in the middle of the overall range commonly cited for till (Freeze and Cherry, 1979, table 2.2; Stephenson and others, 1988, table 2) and are at least an order of magnitude greater than values reported by Prudic (1986, p. 20-23) for unfractured till derived from sedimentary rocks at the West Valley, N.Y. low-level radioactive-waste disposal site. Six Connecticut samples believed to represent the ablation facies of the surface till derived from sedimentary rocks all had hydraulic conductivities in the range of  $4 \times 10^{-1}$  to 2.5 ft/d ( $1.4 \times 10^{-4}$  to  $8.9 \times 10^{-4}$  cm/s). Only one of these values (1.5 ft/d ( $5.3 \times 10^{-4}$  cm/s)) is a vertical hydraulic conductivity. The horizontal hydraulic conductivities of surface till from eight slug tests reported in Melvin and others (in press, table 3) ranged from  $1 \times 10^{-2}$  to 3.4 ft/d ( $3.5 \times 10^{-6}$  to  $1.2 \times 10^{-3}$  cm/s), but the facies is not identified.

Data on other hydraulic properties of southern New England tills compiled by Melvin and others (in press, table 3) includes values of total porosity and specific yield for 15 Massachusetts and Connecticut till samples composed of crystalline-rock detritus and values of total porosity for 58 Connecticut till samples derived from sedimentary rocks. Eleven of the samples derived from crystalline rocks and six of the samples derived from sedimentary rocks are believed to represent the surface till; the rest are identified as drumlin till. The porosity of the tills derived from crystalline bedrock ranged from 22.1 to 40.6 percent, with a median of about 35 percent, whereas the specific yields of the same till samples ranged from 3.9 to 31.2 percent. The porosity of tills derived from sedimentary rocks ranged from 18 to 40.1 percent, with a median of about 25 percent. All these data are laboratory measurements that pertain to the till matrix and



may not be representative of bulk properties where secondary openings, such as fractures, are present. As an example, the porosity resulting from intergranular pore spaces in fractured till in the Interior Plains Region of Canada ranges from 25 to 40 percent, whereas the porosity resulting only from the fractures is much less than 1 percent (Grisak and others, 1976, p. 320).

### Heterogeneity

Bedinger (1989, p. 14) notes that heterogeneous flow systems composed of geologic units that are discontinuous and variable with respect to physical and hydraulic properties are difficult to characterize with confidence and may not be amenable to prediction of ground-water flow and radionuclide migration. Geologic observations, summarized in this report, indicate that Connecticut tills have many sedimentological and structural features that can produce significant differences in hydraulic properties areally (heterogeneity) as well as locally at a given point (anisotropy).

Reliable information on bulk hydraulic properties of till will be needed for scales typically ranging from tens of feet to at least several hundred feet for evaluating containment and transport of low-level radioactive waste in thick-till deposits. The existing data reviewed for this report contains little information on heterogeneity and anisotropy at these scales. Pietras (1981, table 10) determined that the saturated horizontal hydraulic conductivity of drumlin till below the solum at nine sites located along a 1,000-ft (305-m) segment of hillside (shown in fig. 5) was  $2.4 \times 10^{-2}$  to  $1.2 \times 10^{-1}$  ft/d ( $8.5 \times 10^{-6}$  to  $4.2 \times 10^{-5}$  cm/s). Three measurements of the hydraulic conductivity of the solum, however, were considerably higher (2.4 to 3.6 ft/d or  $8.5 \times 10^{-4}$  to  $1.3 \times 10^{-3}$  cm/s). Torak (1979, table 1) determined that the saturated horizontal hydraulic conductivity of shallow (maximum depth 21.5 ft (6.6 m) below land surface) surface-mixed zone (?) and drumlin till at nine sites in eastern Connecticut, all within a radius of about 1.25 mi (2 km), was  $5.4 \times 10^{-3}$  to 1 ft/d ( $1.9 \times 10^{-6}$  to  $3.5 \times 10^{-4}$  cm/s).

The data on heterogeneity of hydraulic conductivity in the vertical direction are for spatial scales of feet to tens of feet. Vertical profiles of laboratory-determined saturated hydraulic conductivity of samples of tills derived from crystalline rocks in eastern Connecticut, reported by Pelletier (1982), are shown in figure 7A-C. These values are reportedly for vertically oriented cores (H.D. Luce, University of Connecticut, oral commun., 1989) and are, therefore, probably vertical hydraulic conductivities.

The eight profiles represent the ablation facies of the surface till (fig. 7A), basal facies of the surface till (fig. 7B), and the drumlin till (fig. 7C) and include samples from the solum (A and B horizons) and underlying parent material (C horizon). In all profiles, except for one that is believed to be the basal facies of the surface till (Montauk 2 profile), hydraulic conductivity is higher near land surface in the solum horizons than below the solum. The vertical hydraulic conductivities of the samples collected for the deepest drumlin-till profile (Paxton 1 in fig. 7C) differ little with depth below the solum, ranging from  $2.0 \times 10^{-1}$  to 2.1 ft/d ( $7 \times 10^{-5}$  to  $7.5 \times 10^{-4}$  cm/s).

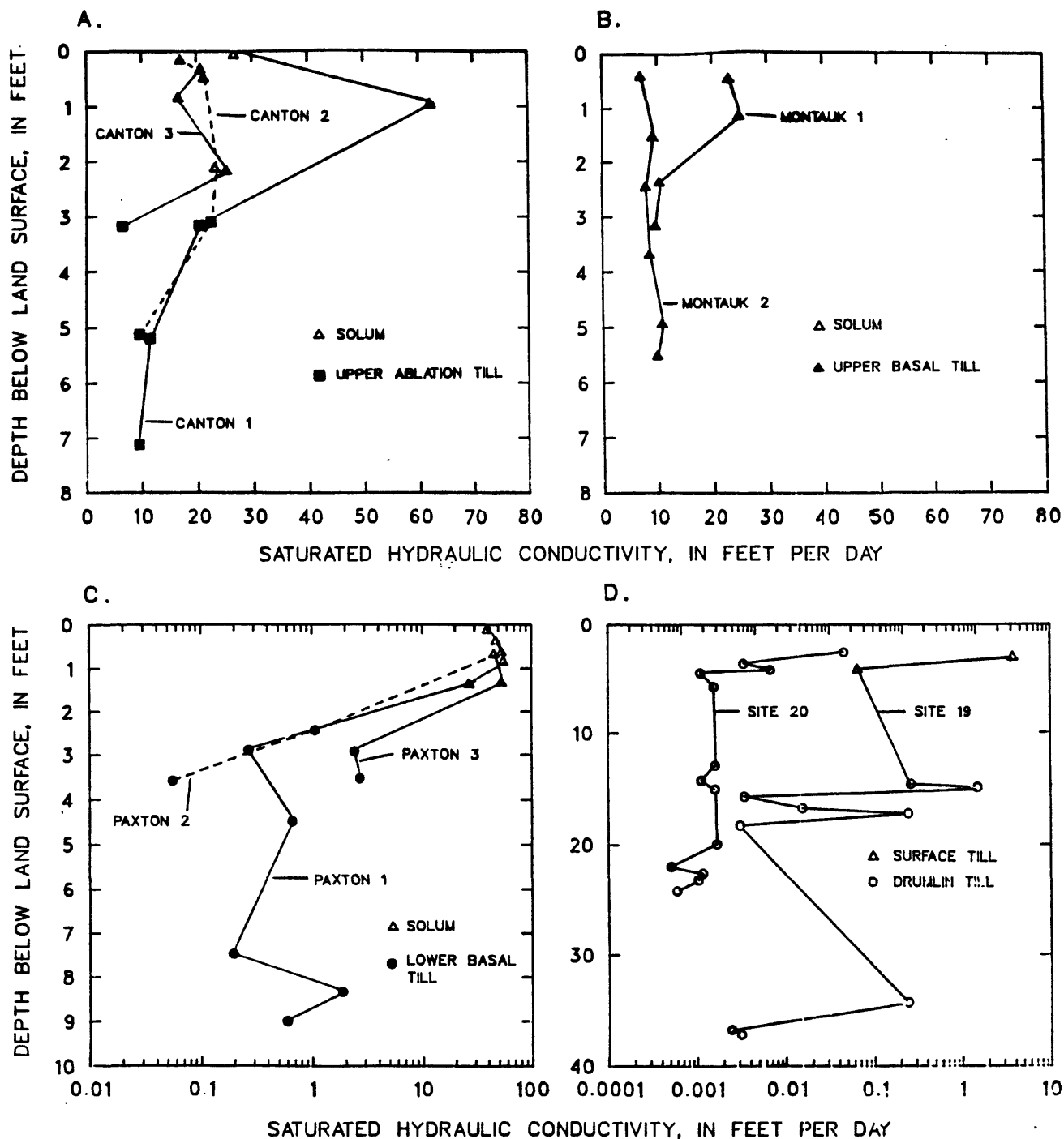


Figure 7.--Vertical profiles of hydraulic conductivity for:

- A. ablation facies of surface till derived from crystalline bedrock (Canton soil),
- B. basal lodgement facies of surface till derived from crystalline bedrock (Montauk soil),
- C. drumlin till derived from crystalline bedrock (Paxton soil), and
- D. drumlin till derived from sedimentary bedrock.

[Profiles A-C from Pelletier (1982, fig. 8); profile D constructed from data in Melvin and others (in press, table 3, sites 19 and 20)]

Profiles constructed from laboratory-determined, vertical hydraulic conductivities of till derived from sedimentary rocks in central Connecticut are shown in figure 7D. All samples at these sites, with the exception of the two upper samples at site 19, are believed to be drumlin till. Site 19 is also located on a drumlin that has significant stratified sediment at depth, although the samples did not appear to contain material other than till. The vertical hydraulic conductivities at site 20 change little below a depth of 5 ft (1.5 m), whereas, at site 19, hydraulic conductivities differ considerably with depth. At both of these sites, hydraulic conductivities are high at shallow depths. The only conclusions that can be drawn from these data are (1) the materials within about 5 ft (1.5 m) of land surface that have been subject to weathering and other soil-forming processes commonly have much higher hydraulic conductivities and (2) the vertical hydraulic conductivity of the till generally decreases or remains nearly constant with depth, although considerable heterogeneity may be present at some sites.

### Anisotropy

If the hydraulic properties of till are independent of the direction of measurement at any given point, the till would be isotropic with respect to hydraulic properties at that point. Conversely, if the properties differ with the direction of measurement, the till is anisotropic at that point. Tills in Connecticut commonly show physical features that could result in anisotropy. Basal (lodgement) facies, for example, have a grain fabric developed during deposition, and fractures, where present, are commonly described as having a preferred orientation parallel or subparallel to the land surface. Torak (1979, p. 88) concluded that tills in eastern Connecticut were anisotropic on the basis of laboratory-determined values of horizontal hydraulic conductivity that were about an order of magnitude greater than vertical values. A comparison of the laboratory-determined values of horizontal and vertical hydraulic conductivities of till samples derived from sedimentary rocks that largely represent drumlin till (Melvin and others, in press, table 3) indicates that horizontal and vertical values are similar. These type of comparisons, however, are not reliable measures of anisotropy with respect to hydraulic conductivity or other hydraulic properties because the values of horizontal and vertical hydraulic conductivity were not obtained at the same location. Data on horizontal and vertical hydraulic conductivity of the same mass of till were not found in our review of existing information, and the degree of anisotropy of Connecticut tills is, therefore, unknown.

### Flow of Water Through Till

Information on the subsurface movement of water is fundamental to understanding the fate and transport of contaminants. For many contaminants, other information about physical, chemical, or biological processes that affect their fate and transport is also required to make reliable predictions. Our present knowledge of hydraulic properties of till is limited and it is not possible to reliably estimate the rate and velocity of water movement through any specific area of thick till. The lack of information about hydraulic properties of till in the unsaturated zone and about the presence or absence of secondary permeability and porosity are perhaps the most critical elements preventing such estimates.

The available data on the hydraulic properties and measured hydraulic gradients in till can be used to estimate the average linear velocity of water movement through the intergranular matrix of a saturated homogeneous mass of till. A simple one-dimensional equation based on Darcy's law is given in Freeze and Cherry (1979, p. 71) as

$$\bar{v} = \frac{K}{n} \frac{dh}{dl}$$

where  $\bar{v}$  is the average linear velocity, in feet per day;  
 $K$  is the saturated hydraulic conductivity, in feet per day;  
 $n$  is the intergranular porosity, dimensionless; and  
 $\frac{dh}{dl}$  is the hydraulic gradient, in foot per foot.

Table 3 shows the total distance traveled along a linear flow path in 100 years for water moving through the saturated, homogeneous till matrix for a range of hydraulic conductivities, total porosities, and hydraulic gradients. The values of hydraulic conductivity, porosity and hydraulic gradients are representative of the low, average, and high values reported in the reviewed literature. A 100-year period was selected because of the general requirement for long-term isolation of low-level radioactive waste and because of the Connecticut Hazardous Waste Management Service's preference for a site with hydrogeology that is not highly vulnerable (Connecticut Hazardous Waste Management Service, 1990, p. A-30). Their definition of highly vulnerable, taken from the the U.S. Environmental Protection Agency, is as follows: "Hydrogeology is considered vulnerable when ground-water travel time along any 100-foot flow path from the edge of the engineered containment structure is less than approximately 100 years." (Connecticut Hazardous Waste Management Service, 1990, p. A-31).

The data reviewed in this report indicate that typical hydraulic conductivities and porosities of the intergranular matrix of Connecticut tills derived from crystalline rocks are close to  $8.5 \times 10^{-2}$  ft/d ( $3 \times 10^{-5}$  cm/s) and 35 percent, respectively. The corresponding typical values for Connecticut tills derived from sedimentary rocks are about  $8.5 \times 10^{-3}$  ft/d ( $3 \times 10^{-6}$  cm/s) and 25 percent. For these typical values and the range of hydraulic gradients used in table 3, water would move from about 12 to 2,216 ft (3.7 to 675 m) through a till in 100 years. If the tills were fractured throughout the flow domain, porosities of the fractures could be considerably less than 0.01 (1 percent) (Grisak and others, 1976, p. 320). For porosities of this magnitude, the distance water would travel throughout the saturated till over a 100-year period would be much greater than shown in table 3, assuming the same range of hydraulic conductivities and hydraulic gradients.

The calculations used in constructing table 3 assume that the flow path is entirely through thick till, from areas of recharge to sites of discharge. In most thick-till areas in Connecticut, however, the bedrock is less than 100 ft (30 m) below the water table. Where gradients are vertically downward, it is very likely that flow would be downward through the till to the bedrock, laterally through the bedrock, and then upward through till and (or) stratified drift to a point of discharge. The calculations also do not consider flow of water through the unsaturated zone, and all the distances in table 3 are for flow paths that begin at the water table.

Table 3.--Estimated distance that water would flow through a homogeneous till matrix during a 100-year period  
[ft/d, feet per day]

Hydraulic conductivity (ft/d)	Porosity (dimensionless)	Hydraulic gradient (foot per foot)			
		0.01	0.05	0.1	0.25
		Flow path distance in feet			
$8.5 \times 10^{-4}$	0.2	2	8	16	39
	.25	1	6	12	31
	.3	1	5	10	26
$\frac{1}{8.5} \times 10^{-3}$	.2	16	78	155	388
	$\frac{1}{.25}$	12	62	124	310
	.3	10	52	103	259
$\frac{2}{8.5} \times 10^{-2}$	.2	155	776	1,551	3,878
	.3	103	517	1,034	2,585
	$\frac{2}{.35}$	89	443	886	2,216
$8.5 \times 10^{-1}$	.2	1,553	7,760	15,520	38,799
	.3	1,035	5,173	10,346	25,866
	.35	887	4,434	8,868	22,171

1/ Values of hydraulic conductivity and porosity considered typical of compact (basal) surface till and drumlin till derived from sedimentary bedrock.

2/ Values of hydraulic conductivity and porosity considered typical of compact (basal) surface till and drumlin till derived from crystalline bedrock.

## SUMMARY AND CONCLUSIONS

The hydrogeologic conditions at any specific thick-till site in Connecticut cannot be predicted from current information. However, the available information does provide insight on the likely range of selected physical and hydraulic properties within which values from a site may be expected to lie.

Two till deposits, which are correlated with two different glaciations and which contrast in physical and hydraulic characteristics and distribution, are recognized in Connecticut. The late Wisconsinan surface till forms an irregular mantle over bedrock and is generally less than 15 ft (4.6 m) thick. The surface till includes compact facies (subglacial lodgement and meltout tills) in most areas and a loose sandy facies (supraglacial meltout till) at the land surface locally. On crests of drumlins, the surface till is a mixed-till zone, containing fragments of the underlying older till in a sandy surface-till matrix.

The Illinoian compact till which forms the bulk of drumlins and other thick-till areas is referred to descriptively as the drumlin till. Drumlin till is generally thicker than 15 ft (4.6 m), commonly more than 100 ft (30 m) thick in drumlins, and as much as 200 ft (61 m) thick. The 1,573 drumlins identified in Connecticut contain thick till and do not contain bedrock outcrops. The drumlin till is weathered and oxidized to depths of 20 to 37 ft (6.1 to 11.3 m). The weathered zone is part of a well-developed interglacial soil, the upper parts of which were removed by late Wisconsin glacial erosion. In drumlins, the surface mixed-till zone overlies weathered drumlin till, which, in turn, overlies thick, nonweathered drumlin till. The distribution of soils that are developed in the mixed-till zone on the crests of drumlins, and soils that are developed in typical surface till on the lower slopes of drumlins support the stratigraphic model.

In the central lowland of Connecticut, the surface and drumlin tills are both relatively fine-grained and red to reddish brown in color. The red drumlin till is identified on the basis of fissility and joint structures, iron-manganese stain on joints, and the relative degree of compaction and low water content. The weathered zone in red drumlin till has not been characterized by laboratory studies.

The drumlin till is inferred to form the bulk of typical drumlins in the central lowland. Thick masses of silt and clay, sand, and gravel have been described in the cores of two drumlins, and discontinuous lenses of stratified materials are present within other thick-till deposits. The presence of similar stratified materials in thick-till deposits cannot be accurately predicted at present. South of Hartford in the lowland, compact surface till locally overlies extensive deposits of stratified silt, clay, and sand. Surface till may underlie small drumlins in the southern part of the central lowland.

Tills in Connecticut are compositionally variable and are related to the local bedrock source. In most crystalline-rock areas, the surface till is notably sandy; however, till derived from marble and schist is silty. In the central lowland, the red to reddish-brown surface till is a silty sand, less stony and more compact than surface till in the uplands. The red surface till is exceptionally clayey in some areas where underlying clay was incorporated into the till.

The drumlin till derived from crystalline rocks is a silty sand; clay content is generally more than 10 percent and as much as 25 percent. Drumlins derived from marble and schist generally contain more than 50-percent combined silt and clay. The drumlin tills derived from marble and schist are similar in grain-size distribution and degree of compaction to the silty and clayey varieties of red surface till. Drumlins are very compact and appear massive and homogeneous in deep exposures. Fractures are numerous and closely spaced in the upper part of the weathered zone in drumlin till. The till fissility is not apparent in lower parts of deep exposures, but dried samples of the till part along subhorizontal surfaces.

The information on recharge in thick-till areas, although scant, suggests that rates of several inches per year are likely. Rates of more than 1 in/yr (2.5 cm/yr) reportedly can pose difficulty for disposal of low-level radioactive wastes above the water table in materials with low permeability and specific yield.

Depth to the water table is likely to be 10 to 15 ft (3 to 4.6 m) below land surface but at many sites may frequently rise to within 5 ft (1.5 m) of land surface. Fluctuations of about 8 to 17 ft (2.4 to 5.2 m) are to be expected over periods of several years and greater fluctuations are possible. Information on the water table does not include the capillary fringe, which can be thick in fine-grained materials, such as till, and can affect the flow of water and transport of contaminants.

Major flow paths through thick till in the saturated zone are likely to range from a few hundred to several thousand feet, but small flow systems with much shorter flow paths of a few feet to a few tens of feet may be locally present. Ground water in recharge areas where hydraulic gradients are vertically downward is likely to flow from the till into underlying bedrock before it ultimately discharges.

The horizontal hydraulic conductivities of Connecticut tills derived from crystalline rocks are commonly about  $4 \times 10^{-2}$  to 24 ft/d ( $1.4 \times 10^{-5}$  to  $8.5 \times 10^{-3}$  cm/s) based on field and laboratory measurements from eastern Connecticut. These values are at the upper end of the overall range commonly cited for till. The porosity and specific yield of tills of similar provenance ranged from 22.1 to 40.6 percent and from 3.9 to 31.2 percent, respectively. The horizontal and vertical hydraulic conductivities of compact Connecticut tills derived from sedimentary rocks are commonly about  $1 \times 10^{-3}$  to  $6.2 \times 10^{-2}$  ft/d ( $3.7 \times 10^{-7}$  to  $2.3 \times 10^{-5}$  cm/s) based on laboratory measurements on till samples from central Connecticut. These values are near the middle of the overall range commonly cited for till. The porosity of the tills derived from sedimentary rock ranged from 18 to 40.1 percent. Most of the cited hydraulic conductivities are for tills that are believed to be either the compact facies of the surface till or the drumlin till. The field measurements of hydraulic conductivity may approximate values for the bulk mass of the till. The laboratory measurements of hydraulic conductivity and porosity, however, apply only to the till matrix and may differ from values that represent the bulk mass of the till. There are presently no reliable data on hydraulic anisotropy of tills in Connecticut.

In most recharge areas of thick till where hydraulic gradients are downward, the flow path from the water table to the bedrock is likely to be 100 ft (30.5 m) or less. A simplified analysis of water movement through a homogeneous till matrix indicates that movement of more than 100 ft (30 m) in a 100-year period is likely for hydraulic conductivities equal to or greater than  $8.5 \times 10^{-3}$  ft/d ( $3 \times 10^{-6}$  cm/s) where hydraulic gradients are equal to or exceed 0.1 and porosities are 0.2 to 0.35 (20 to 35 percent). Conversely, for lower hydraulic conductivities and (or) lower hydraulic gradients, water movement could be only a few feet in 100 years.

A major concern at any thick-till site is the heterogeneity of the subsurface materials and how this heterogeneity affects the spatial variability of hydraulic properties. The presence, extent, and continuity of fractures and lenses or layers of stratified drift are particularly difficult to define in tills, particularly in the deeper parts of thick-till deposits. Heterogeneity increases the uncertainty in model predictions of contaminant transport and makes it difficult to adequately characterize, model, analyze, and monitor a site. No study of the spatial variability of the bulk hydraulic properties of Connecticut tills has been conducted. The available data on hydraulic conductivity and porosity of the till matrix indicate these properties may be relatively heterogenous or homogeneous at a site.

Many other elements of the hydrogeology of thick till in Connecticut that affect contaminant migration have been subject to little or no study. These elements include the structural and sedimentological features in the deeper parts of thick-till deposits, hydrology of the unsaturated zone, recharge and its variability in space and time, head distribution and flow paths within the saturated zone, and many of the physical and chemical properties that control how contaminants are transported and how they are partitioned between dissolved and solid phases. This lack of general knowledge will necessitate more comprehensive site-characterization studies. The duration of such studies may also have to be extended because of the poor understanding of time-dependent processes such as infiltration and recharge.



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Appendix A. Specific site-suitability requirements that relate to hydrogeology (Code of Federal Regulations, Chapter 10, Part 61, U.S. Nuclear Regulatory Commission, 1982).

1. The disposal site shall be capable of being characterized, modeled, analyzed, and monitored.
2. Within the region or state where the facility is to be located, a disposal site should be selected so that projected population growth and future developments are not likely to affect the ability of the disposal facility to meet the performance objectives.
3. Areas must be avoided having known natural resources which, if exploited, would result in failure to meet the performance objectives.
4. The disposal site must be generally well-drained and free of areas of flooding or frequent ponding. Waste disposal shall not take place in a 100-year floodplain, coastal high-hazard area or wetland.
5. Upstream drainage must be minimized to decrease the amount of runoff which could erode or inundate waste disposal units.
6. The disposal site must provide sufficient depth to the water table that ground-water intrusion, perennial or otherwise, into the waste will not occur. The Commission will consider an exception to this requirement to allow disposal below the water table if it can be conclusively shown that disposal-site characteristics will result in molecular diffusion being the predominant means of radioactive movement and the rate of movement will result in the performance objectives being met. In no case will waste disposal be permitted in the zone of fluctuation of the water table.
7. The hydrogeologic unit used for disposal shall not discharge ground-water to the surface within the disposal site.
8. Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or vulcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objective, or may preclude defensible modeling and prediction of long-term impacts.
9. Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, landsliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objective, or may preclude defensible modeling and prediction of long-term impacts.
10. The disposal site must not be located where nearby facilities or activities could adversely impact the ability of the site to meet the performance objectives, or significantly mask the environmental monitoring program.